2018

LIFE-CYCLE-COST EVALUATION OF BRIDGES WITH FIBER-REINFORCED POLYMERS (FRP)

Annika Juliane Haak
University of Rhode Island, Annikahaak@gmx.net

LIFE-CYCLE-COST EVALUATION

OF BRIDGES WITH

FIBER-REINFORCED POLYMERS (FRP)

BY

ANNIKA JULIANE HAAK

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

CIVIL AND ENVIRONMENTAL ENGINEERING

UNIVERSITY OF RHODE ISLAND

2018

MASTER OF SCIENCE THESIS

OF

ANNIKA JULIANE HAAK

APPROVED:

Thesis Committee:

Major Professor George Tsiatas

Sumanta Das

Arun Shukla

Nasser H. Zawia
DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND
2018

ABSTRACT

Life-cycle costs (LCC) and environmental impacts of bridges have gained in importance over the past decades. Therefore, a life-cycle cost analysis should be an essential component of the bridge design decision-making.

The objective of this thesis is to compare a FRP bridge deck with a reinforced concrete deck and compile the different costs that appear during the whole life-cycle of a bridge through a computational software. Computational methods help to understand and predict the impact of uncertain factors on a whole life-cycle cost analysis is essential. To obtain an overview of the topic, commonly used materials are introduced and basic knowledge of FRP is imparted. Additionally, terms such as LCC and life-cycle assessment (LCA) are defined and methods of performing analysis to determine these are explained. LCC Analysis is used to develop a cost compilation of all costs during the life-cycle and pay respect to cost sensitivity. LCA is used to obtain the impact of a design on the environment. These impacts are assigned with estimated environmental costs. Computational software for implementation of these analysis are implemented.

A full life-cycle cost analysis is conducted in this work using the software BridgeLCC 2.0 by NIST. All cost items and unit amounts throughout the life-cycle are implemented and assigned with uncertainties. The analysis is followed by a comparison and discussion of results.

The obtained results show qualitative correspondence with trends that were predicted in the literature for the material's future. The longer the bridge design life, the more FRP is catching up to reinforced concrete bridge decks and is therefore a

competitive alternative. Especially, when taking user costs into consideration, a positive impact on costs of the roadway user is perceived. Additionally, environmental costs included to the LCCA, show the clear advantages of FRP over reinforced concrete.

ACKNOWLEDGMENTS

I would first like to express my gratitude to my major professor and thesis advisor, Dr. George Tsiatas of the Civil and Environmental Engineering faculty at the University of Rhode Island. The door to Prof. Tsiatas office was always open and I could always expect help, useful comments, remarks and engagement throughout my academic time at the University of Rhode Island. He supported me in the best way a professor could.

Furthermore, I would like to thank my committee members, Dr. Sumanta Das and Dr. Arun Shukla for their encouragement, insightful comments, and commitment. My whole committee has given me the chance to research on a highly professional level. I also want to thank the Rhode Island Marine Trades Association for their great financial support throughout the first phase of the research of which the topic of my thesis has developed from.

I would also like to thank the University of Rhode Island and the Technische Universität Darmstadt for the existence of a Dual Degree Master Program that offered me the opportunity to successfully complete my studies at the University of Rhode Island. I am very grateful for this opportunity and therefore wish to thank the international Engineering Program at the University of Rhode Island, the Office of international students and scholars at the University of Rhode Island, the International Office of my home university, Technische Universität Darmstadt, the program coordinators Dr.-Ing. Kaja Boxheimer, Marie-Christin Wedel and Dr. Sigrid Berka.

Finally, I would like to thank my family for their great support throughout the whole academic year abroad. Especially I must express my gratitude to my parents who

always were great inspiration, my mother who has always been there support and strengthen me in any way possible and my father who has always led me through my whole life and who has always been very supportive and made my several study-abroad years possible.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE **PAGE**

LIST OF TABLES

TABLE **PAGE**

LIST OF EQUATIONS

LIST OF ACRONYMS

1.4-DCB	1.4-dichlorobenzone
ADT	Average daily traffic
ADTT	Average daily truck traffic
Alt 1	Alternative 1
BC	base case
C2H2	Acetylene
CALTRANS	California Department of Transportation
CFK-11	trichlorofluoromethane
CPI	Consumer Price Index
CO_2	carbon dioxide
DOT	Department of Transportation
e.g.	exempli gratia = for example
EP	epoxy resin
etc.	et cetera
FHWA	Federal Highway Association
FRP	Fiber-Reinforced Polymer
LCA	life-cycle assessment
LCC	life-cycle cost
LCCA	life-cycle cost analysis
LCI	life-cycle inventory analysis
LCIA	life-cycle impact assessment

NBI	National Bridge Inventory
NIST	National Institute of Standards and Technology
NPV	net present value
NTM	new technology materials
OM&R	Operation, Maintenance and Repair
PO4	phosphate
RI	Rhode Island
RIDOT	Rhode Island Department of Transportation
RIMTA	Rhode Island Marine Trades Association
Sb	antinomy
SD	structurally deficient
SO_2	sulphur dioxide
UP	unsaturated polyester resin
US	United States of America
UV	ultraviolet
VOC	vehicle operating cost
WSDOT	Washington State Department of Transportation
PAN	polyacrylonitile

LIST OF UNITS

€	Euro
$	US-Dollar
MPa	megapascal
mph	miles per hour

GPa	gigapascal
%	percent
cm	centimeter
°C	Celsius
°F	Fahrenheit

CHAPTER 1

INTRODUCTION

1.1. Justification for this Study

Bridge infrastructure is aging rapidly in the United States along with numerous other countries. Depending on environmental conditions, climate, location and usage, bridges face problems such as deck deterioration, scour at bridge substructure when the bridge is in contact with flowing water, corrosion of steel or of steel reinforcement in concrete, as well as problems due to dynamic response (wind or earthquake), aging and deterioration of materials.

The Federal Highway Administration (FHWA) tracks the condition of major bridge components, such as decks, superstructures and substructures from a scale 0 (failed) to 9 (best). Data are available in the National Bridge Inventory (NBI). According to the Department of Transportation's National Bridge Inventory Database, there are about 615,000 bridges in the United States out of which 54,560 are characterized as Structurally Deficient (SD) meaning that at least one of a set of metrics (deck, superstructure, substructure, structural evaluation or waterway adequacy) received a rating less than or equal to 4. Starting January 1, 2018 a new classification system was introduced characterizing bridge condition as good, fair, or poor. The new system looks only at ratings of deck, superstructure and substructure. For a bridge to be in good condition all ratings for these three parts of the bridge must be no lower than seven (7). If any of these ratings is four (4) or lower, the condition of the bridge is characterized as poor. Based on the new classification system, a total of 47,619 bridges nationwide are characterized as poor.

Figure 1 shows the percent of bridges that have been characterized as structurally deficient in every single state. Based on the Federal Highway Administration's 2017 bridge report, Rhode Island is the leading state in structural deficient bridges (FHWA 2017). Out of 778 bridges in the state of Rhode Island 181 (or 23%) have been characterized as structurally deficient. Following the new classification 131 bridges are considered "good", 466 "fair" and 181 "poor". This is compared with an average number of "poor" bridges for all states at 7.9%. If bridge funding continues at its current level, in 20 years 40 to 50% of all bridges in Rhode Island will be rated as structurally deficient (Martin 2015; Pipinato 2015).

A recent federal estimate puts the backlog of rehabilitation projects for bridges in the US at $123 billion. To eliminate this backlog over the period from 2012 to 2032 an annual investment of $24.6 billion is estimated (Kirk and Mallett 2018).

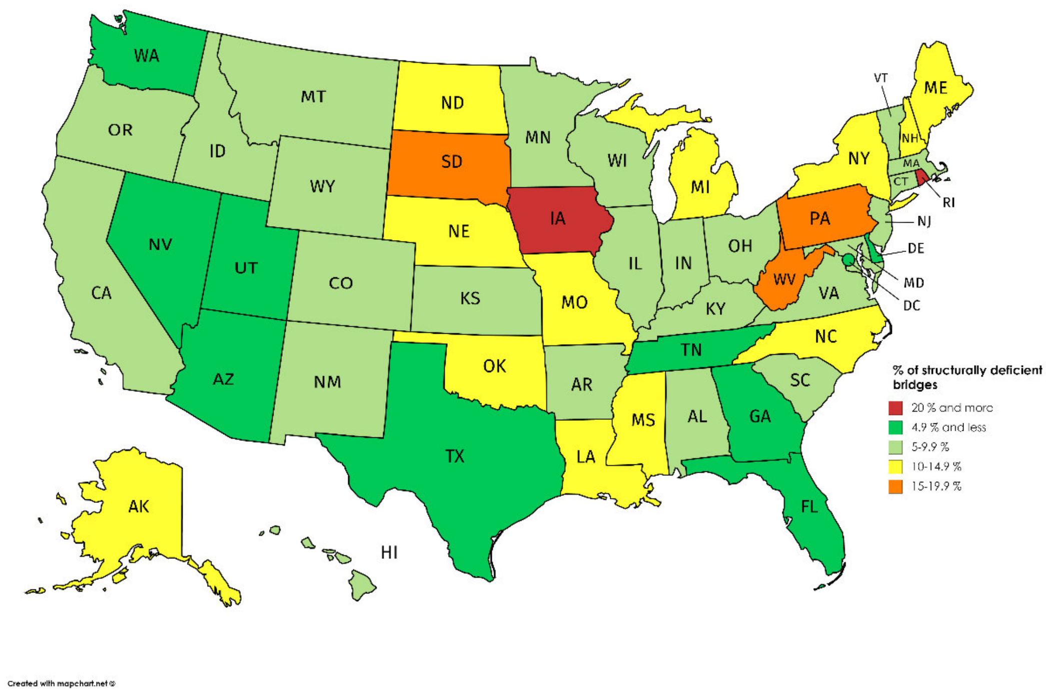

Figure 1 - Percentage of structurally deficient bridges in the U.S.

A large percentage of bridges in Rhode Island as well as many other states, need to be repaired or even demolished to be completely rebuilt. Due to the high number of affected bridges, needed measures come along with enormous expenses that states cannot bear. At the same time, an opportunity is provided to use materials, systems and methods that will result in long lasting, low maintenance bridges at a reasonable life-cycle cost (LCC).

Traditionally, bridges have been constructed with materials such as steel, reinforced and/or prestressed concrete, timber and masonry. These materials have served as effective materials in bridge engineering over many centuries. However, due to the upcoming challenges of an extensive bridge repair and reconstruction program newer materials should be considered and used when it is deemed appropriate. Composite materials, such as fiber-reinforced polymers (FRP), have been used for a long time in applications including the shipping and the aerospace industries. Recently there are efforts to use such materials for infrastructure applications including highway bridges.

In Rhode Island there is a robust boat construction industry using composite materials. The collective expertise of these companies could be used outside of their traditional products. As the Rhode Island Department of Transportation (RIDOT) is initiating an extensive bridge repair and reconstruction program it is wise to consider composite materials in addition to the traditional bridge construction materials such as steel and reinforced or prestressed concrete.

Recently, an extensive literature review of bridge construction practices using composite materials in the US and around the world was carried out at the University of Rhode Island. The effort was funded by the Rhode Island Marine Trades Association (RIMTA), and supported by the Composites Alliance of RI, Commerce RI, RIDOT, and local bridge engineers. This is an early step in evaluating the use of FRP in bridge constructions. The developed knowledge in this phase of the research will help progress practical implementation of usage of composite materials in Rhode Island. Key objectives of the first phase included collecting information on the use of composite materials worldwide, based on specific applications appropriate to the needs of the State of Rhode Island and an evaluation of the gathered information on advantages and disadvantages or limitations of composite materials in bridge deck and superstructure designs.

The initial study revealed a lack of life cycle cost analysis (LCCA) and life cycle assessment (LCA) for bridges constructed with composite materials. This is an important aspect to consider given cost of the upcoming bridge repair/reconstruction program. Therefore, the present work will focus on the costs associated with using FRP materials in bridge applications including their environmental effects as compared with conventional materials used in bridge constructions.

1.2. Objective

The objective of this thesis is to compile the different costs that compile during the whole life of a bridge. This thesis only focuses on bridge decks of highway bridges. Once all costs are collected and put into categories, a LCCA can be performed. Uncertainties are assigned to every unit cost and unit measure. Additionally, uncertainties can be added to the frequency. Events are assigned to cost items that could be affected by the occurrence of the event. The same procedure will then be applied for bridges made of conventional materials. After, results of both approaches mentioned above will be compared and discussed. The influences of an increase or decrease of several factors are displayed. The section limitation of this study is followed by a conclusion.

1.3. Hypothesis

The evaluation of two hypotheses will be elaborated in chapter 5, and reviewed in chapter 6 of this thesis.

The hypothesis of this thesis is that with a full LCC evaluations, involving social, environmental and economic elements the economic viability of FRP, compared with conventional materials, is proven. FRP will be more competitive for future designs. Additionally, the importance of including environmental impacts, computed with an LCA, will be stated and then implemented in LCCA for a realistic design comparison. In previous LCCA, social and environmental factors such as design criteria are unfortunately often neglected among the construction industry. It is important to convince contractors, that the mentalities of individuals have moved towards a more environmentally conscious lifestyle. This ongoing change will influence the construction industry increasingly so that not only initial costs are a decision-making criterion in competitive bidding. Influences of a design on the society and environment gain in popularity when choosing from different designs in biddings.

1.4. Organization of Thesis

This thesis offers an overview about used materials and materials that are taken into consideration for bridge deck repair measures as well as materials for bridge designs. Additionally, it compiles the costs of the whole life-cycle of a bridge and the impacts of materials used for the design. Therefore, the components' importance of life-cycle cost analysis (LCCA) and life-cycle assessments (LCA) are defined and described. When merging costs and sustainability, it will unveil a possible change in the construction and planning sector in the close future.

The second chapter contains a literature review on conventional materials and introduces FRP as a construction material. It explains the composition of the raw materials that FRP is made of. Additionally, the bonding of the materials is explained. Advantages and disadvantages of FRP are presented at the end of this chapter.

The terms LCC, LCCA and LCA are introduced in the third chapter. Various components that form LCC are mentioned and explained. When evaluated, the influences of FRP on the environment, the region and the user can be evaluated in an LCCA and LCA.

Chapter four presents a method and all steps needed to accomplish a full LCCA. It covers the very basic deterministic approach, which does not encounter risks and uncertainties. The sensitivity approach considers the significance and uncertainties in previously made assumptions and includes these deviations to the LCCA. The risk analysis takes over and improves the LCCA where sensitivity approach fails. Furthermore, this chapter ends with an insight view on available computational software.

In chapter 5 whole LCCA including a deterministic approach, sensitivity approach and a risk analysis is performed on bridge deck design alternatives on Canonchet Bridge in Hopkinton, RI. The bridge carries Woodville Alton Road over I-95. The first investigated alternative uses FRP as bridge deck material. This alternative is compared with a conventional reinforced concrete deck. For the analysis the software BridgeLCC 2.0 was used, which is introduced in section 4.2. The final costs with inclusion of uncertainties are posed.

Lastly, chapter 6 summarized the work and the results along with a discussion of the analysis results. Limitations of this study are pointed out for further research and improvement of the analysis method. This if followed by a conclusion stating results.

CHAPTER 2

MATERIALS

2.1. Conventional Materials

As mentioned in the previous chapter there are about 615,000 bridges in the United States of America. For about a third of all bridges steel was used for the design. Conventional reinforced concrete was used for 235,000 bridges and 108,000 bridges were constructed using prestressed concrete (National Association of Corrosion Engineers). The graph in Figure 2 shows the distribution of construction materials between 1950 and 1995. Noticeable, steel was used as the main construction material in the 20th century. A clear peak of newly built steel bridges is noted in 1950. In 1975 prestressed concrete overtook the market. In the late 1990s prestressed concrete bridges dominated the market with a share of about 60% with a prospect of increased use in bridge constructions in the future. In the following sections materials used for bridge constructions are described.

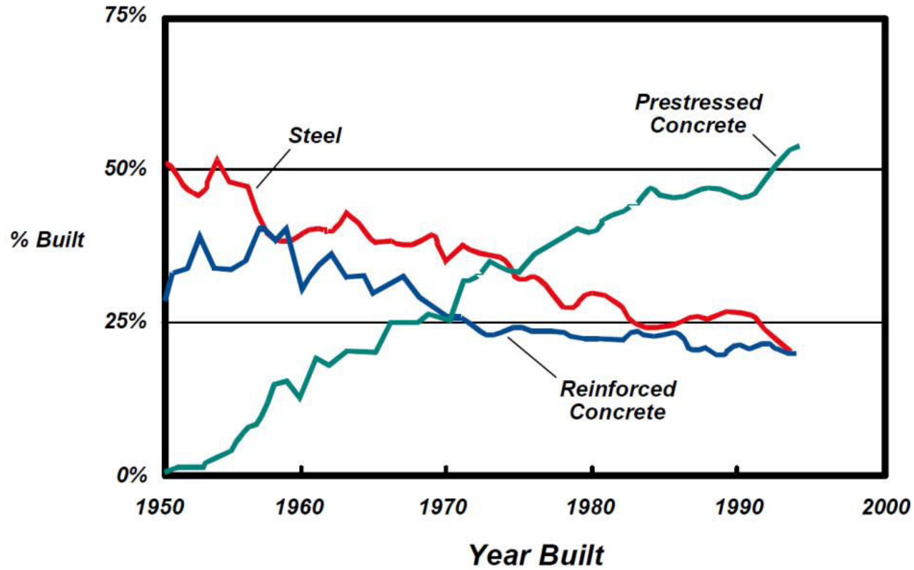

Figure 2 - percentage of used material for annually built bridges (Aktan et al.)

Stones and timber were used in the early days of bridge engineering. Structures primarily were built with stones and timber by trial, error and rule of thumb. As the complexity and increased requirements of structures increased, accurate engineering design methods were developed. The use of stones as construction material for bridges originates in the Roman Empire. Stones were mainly used for arch bridges due to their high compressive strength. Throughout the past centuries stone bridges have proven to be good economical and efficiency factors due to their durability and low maintenance needs.

Wood is another material that is still applied as a material for bridge structures. Nevertheless, the use of wood in bridge engineering comes along with advantages such as high toughness, it is a renewable material and its low density increases its high specific strength. However, wood possesses some problematic properties. A high anisotropy, vulnerability to pests, susceptibility to rot and that it cannot be used in high temperatures, are disadvantages to using timber for bridge designs. Although, timber is used around the world as a construction material for pedestrian bridges.

Steel is taken into consideration for bridge design if long spans are required. Steel properties of tensile strength, ductility and hardness are strongly influenced by the amount and variation of steel elements. Due to its ductility, steel exhibits elastic behavior before it devolves into a plastic state. Therefore, signs of failure are detectable (The Constructor 2017a).

Nowadays, concrete is used in most bridge designs as the primary material. Concrete offers good compressive strength properties but lacks in tensile strength and is susceptible to thermal expansion and shrinkage effects. The failure of concrete occurs without warning signs due to the brittle behavior of the material.

To improve the shortcomings of concrete, engineers developed reinforced concrete in which steel bars are used to strengthen areas in concrete where tension exists. Especially, when seismic loads are likely to occur ductility gains in importance.

Prestressed concrete is preferred and is widely used. When prestressing concrete, permanent stress is created in the structure, which will help the concrete to resist tensile stresses that occur during the actual load condition (The Constructor 2017b). Pretension and post-tension are both established methods to prestress concrete. These methods allow longer clear spans, thinner slabs and fewer beams. Additionally, the occurrence of cracks is reduced, and the durability is increased during freeze-thaw cycles.

2.2. Fiber-Reinforced Polymers

Composite materials are defined as two or more source materials combined into a new material that offers improved properties for a specific application. Composite materials are an established material in the aerospace engineering industry and they have slowly gained popularity in the civil engineering industry. The use of FRP in bridge constructions and repairs has increased over the past few decades. Particularly, bridge decks use FRP as an alternative material. FRP consists of fibers and a matrix. While fibers make up 30 to 70 volumetric percent of FRP, they create 50% of the weight of the composite material (Sonnenschein et al. 2016). Beyond a volume fraction of about 80%, the fibers are not fully surrounded and protected by the matrix (Henkel and Pense 2002). The usage of glass fiber-reinforced polymers (GFRP) for bridge decks allows for a reduction of the deadload of the bridge deck compared to a conventional concrete deck by 80% (Lee et al. 2018). FRP elements are pre-fabricated off-site in a controlled and industrial environment. Pre-fabrication allows for rapid on-site assembly which has a huge impact on user costs as addressed further on in this work.

To calculate the modulus of elasticity of the composite E_C, the equation below can be used, where M and R refers to the matrix and resin, respectively, and f is the volume of fraction.

$$E_C = f_M E_M + f_R E_R \qquad \text{Eq. 1}$$

An approximation of the tensile strength of a composite σ_C can be developed by using the following equation, where σ_M is the tensile strength of the matrix and σ_R is that of the dispersed phase (Henkel and Pense 2002).

$$\sigma_C = f_M \sigma_M + f_R \sigma_R \qquad \text{Eq. 2}$$

2.2.1. Fibers

Fibers are loadbearing components in FRP. Therefore, the mechanical strength of FRP elements relies on fibers, the material used as a fiber, the grade, the shape and the direction. Materials used as fibers for FRP applications are carbon, glass, aramid and basalt (see Table 1). Established materials in the civil engineering industry are carbon and glass.

Table 1 - Mechanical properties of existing fiber material (Sonnenschein et al. 2016)

Property	Unit	E-Glass fibers	Carbon fibers	Aramid fibers
Tensile strength	MPa	3,500	2,600-3,600	2,800-3,600
Young's modulus E	GPa	73	200-400	80-190
Elongation at failure	%	~4.5	0.6-1.5	2.0-4.0
Density	g/cm³	2.6	1.7-1.9	1.4
Coefficient of thermal expansion	10^{-6}/K	5/6	axial -0.1 to -1.3, radial 18	-3.5
Fiber diameter	µm	3-13	6-7	12
Fiber structure		isotropic	anistropic	anistropic

Carbon can be produced from polyacrylonitile (PAN), petroleum or rayon and requires high energy during the production process. However, carbon fiber is not sensitive to aggressive environmental impacts or high temperatures. Additionally, it offers high tensile strengths as well as a high modulus of elasticity. Nonetheless, the fibers exhibit reduced radial strength due to their inherent anisotropy and are subjected to fatigue failure. The material costs of carbon are relatively high which leads to the predominant use of glass as the fiber material for FRP (Mara et al. 2014).

Glass fibers allow the lowest energy consumption during their production compared with steel, concrete and carbon. Among others, glass fibers owe their popularity to chemical inertness. The high melting temperature however, around 1550°C (~2822°F), needs to be considered as an environmental issue due to its high energy intensity. Glass fibers exist in many varieties such as A-glass (soda lime silicate glass), AR-glass (alkali resistant glass), C-glass (calcium borosilicate glass; chemical stability in corrosive acid environments), D-glass (borosilicate glass; low dielectric constant), E-glass (alumina-calcium-borosilicate glass; alkali-free glass; electrically resistant), ECRGLAS® (calcium aluminosilicate glasses), R-glass (calcium aluminosilicate glasses), S-glass (high strength glass; high stiffness, extreme temperature resistant, corrosion resistant) and S2-glass® (magnesium aluminosilicate glass; high strength, modulus and stability) (Hartman et al. 1996). Since E-glass is most widely used, other glass types are mentioned but need no further explanation. E-glass is made from quartz or limestone and therefore, it is naturally unlimited and does not negatively impact the environment. Moreover, E-glass costs about 10% less than carbon fibers (Foster et al. 2000). A clear disadvantage is the low Young's Modulus, a low long-term strength due to stress rupture and a low humidity and alkaline resistance (Mara et al. 2014). Glass fibers in FRP are protected from humidity and alkali attack by the matrix as described in section 2.2.2.

Fibers can be geometrically arranged as either directional or non-directional. Woven, non-woven, grid and mesh-products contain directional fibers while mats and surfacing fleeces belong to the category of non-directional fibers.

2.2.2. Matrix

The matrix in FRP acts as a binder and embeds fibers in their geometric arrangement. Additionally, it protects the sensitive fibers from environmental impacts like humidity or coastal air and prevents buckling of fibers under compressive action. The matrix exhibits viscoelastic stress-strain behavior.

There are two existing categories of matrices. Thermoplastic and thermosetting polymers are created through energy intensive chemical processing. While thermoplastic polymers are mainly used for processing and recyclability reasons, thermosetting polymers are most commonly used for FRP. Thermosetting polymers contain a cross-linked molecular structure and can no longer be formed after hardening or polymerization reaction. Unsaturated polyester resin (UP), epoxy resin (EP) and vinylester resin are types of thermosetting polymers. UP and EP used in FRP composites possess relatively low energy intensities. Furthermore, EP exhibits natural UV radiation protection (Mara et al. 2014). As an alternative to EP, isopolyester could be used as a matrix. Isopolyester offers excellent resistance to moisture and corrosion and therefore, does not require any waterproofing layer. Additionally, it costs less than half of the EP (Foster et al. 2000).

2.2.3. Fiber-Matrix bonding

Adhesion, mechanical compatibility between fibers and matrix, the angle between fibers and the load direction influence the mechanical properties of FRP. The angle between fibers and the load direction determine the stiffness and strength of bonding.

While fibers offer mechanical strength and are the main load-carrying component, resin matrices protect fibers from corrosion in extreme and harsh environments. In Figure 3 the stress-strain behavior of carbon fiber-reinforced polymer (CFRP), glass fiber-reinforced polymer (GFRP) and aramid fiber-reinforced polymer (AFRP) is compared with steel. The importance of the combination of fibers with matrices is visualized in the stress-strain diagram in Figure 4.

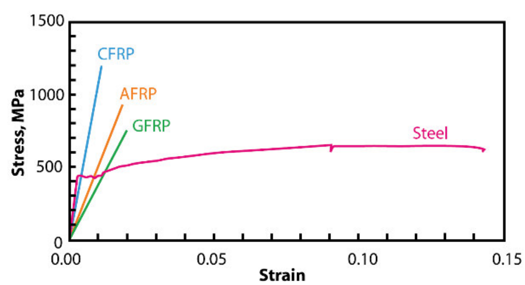

Figure 3 - Stress-strain behavior of CFRP, AFRP, GFRP and Grade 60 Steel (Arnold and Carr 2010)

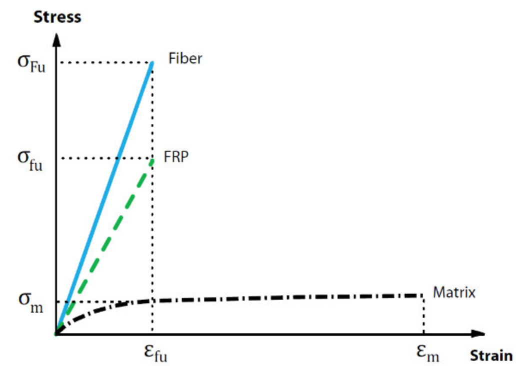

Figure 4 - Stress-strain behavior of FRP components compared to FRP composition (Arnold and Carr 2010)

2.3. FRP Advantages and Concerns

FRP offers various application possibilities to adhere to the needs of a design and can be formed into any shape resulting from its tailorable anisotropy. Mechanical properties of FRP are notably different than those of conventional materials. FRP offer high stiffness, high fatigue, high impact strength, directional strength and dimensional stability. Due to its non-magnetic property, the material possesses a high dielectric strength and acts as an insulator. This is accompanied by its radar transparency. Additionally, FRP exhibits corrosion and frost resistance (freeze-thaw cycles and de-icing salts), low thermal conductivity, long term durability as well as high chemical resistance (Nystrom et al. 2003). Furthermore, FRP possesses of a low coefficient of thermal expansion and exhibits low thermal conductivity so that heat develops 200 times slower in FRP than in conventional materials. Due to long term durability of the material components, there is a minimal maintenance need. One of the most advantageous factors of FRP is the high-strength-to-weight ratio which results in a weight saving potential. This results in an enhancement in seismic resistance, an increased speed of assembly and an immense fabrication time reduction (Karbhari and Zhao 2000). It does not need heavy lifting equipment and requires smaller construction vehicles. FRP elements can be transported easily due to the lightness of the parts, minimized labor costs and saved construction time. A decreased construction time accompanied by a reduced time-period of detours minimizes commerce and traffic disturbances.

Besides the mentioned advantages of FRP, there are some concerns when considering FRP. Despite the mentioned advantages of FRP, there are certain drawbacks when considering FRP. The most notable obstacles are the high initial costs which make FRP often less desirable. Building materials must be safe and a concern can be about a materials strength in the event of a fire. Only a little is known on the loss of strength of the material during the case of fire. Nevertheless, during the case of fire the bearing capacity of glass fiber mesh stays intact if glass fibers are well anchored in the matrix (Mara et al. 2014). Further obstacles are the lack of familiarity in most areas, the lack of comprehensive standards and missing design guidelines. FRP's brittle fracture behavior is problematic in that the element fails without any warning. When FRP is compared to steel, both used in combination with concrete, FRP has a lower thermal compatibility and ductility, which allows larger deformation and energy dissipation between FRP and concrete (Mufti and Neale, Kenneth, W. 2008). The glass fibers are in serious danger of humidity and alkaline attack in the event that they are not protected by the matrix.

Many of these mentioned problematics of FRP can be improved by further research on the material. An investigation of the behavior during the occurrence of fire to determine the fire resistance and further studies on embodied energy and the impact of long-term carbon emission are needed. Data on long term durability, which is of equal importance, is missing, and currently cannot be provided.

CHAPTER 3

LIFE-CYCLE EVALUATION

3.1. Life-Cycle Costs

LCC are the present value of total costs of a product that appear during the entire life span or a specified period. As shown in Figure 5 this includes initial costs, maintenance and repair costs as well as disposal costs. The design life time of a bridge used for LCC evaluation is generally set for 75 to 100 years and is normally shorter than 40 years, which is the life cycle of the pavement (Setunge et al. 2002).

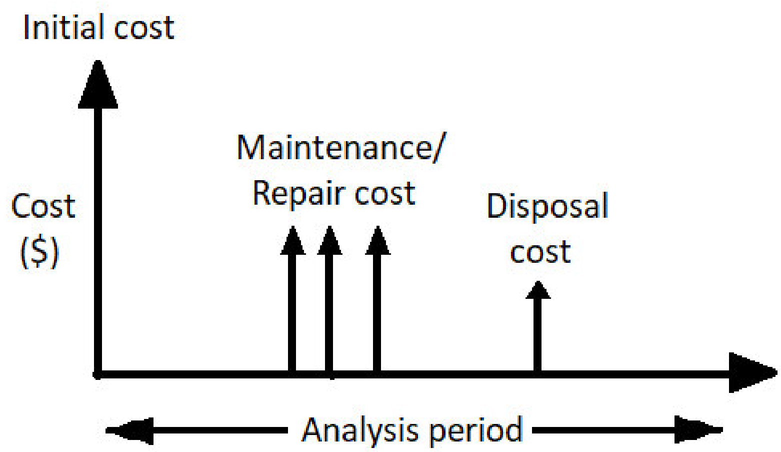

Figure 5 - Stream diagram for a life cycle cost analysis (Setunge et al. 2002)

Costs appearing during the life span of a bridge can be organized under the category of cost bearers, time periods or components. The latter will be neglected in this work since the analysis in chapter 4 only considers the bridge deck as a cost component examined by LCCA separated into two groups, direct and indirect costs as shown in Figure 6. Costs by timing are sub-categorized into initial, operation, repair and maintenance costs as well as disposal costs. Costs by bearer are sub-categorized into direct costs, indirect costs and social costs. The coherence of the different groups is visualized in Figure 6.

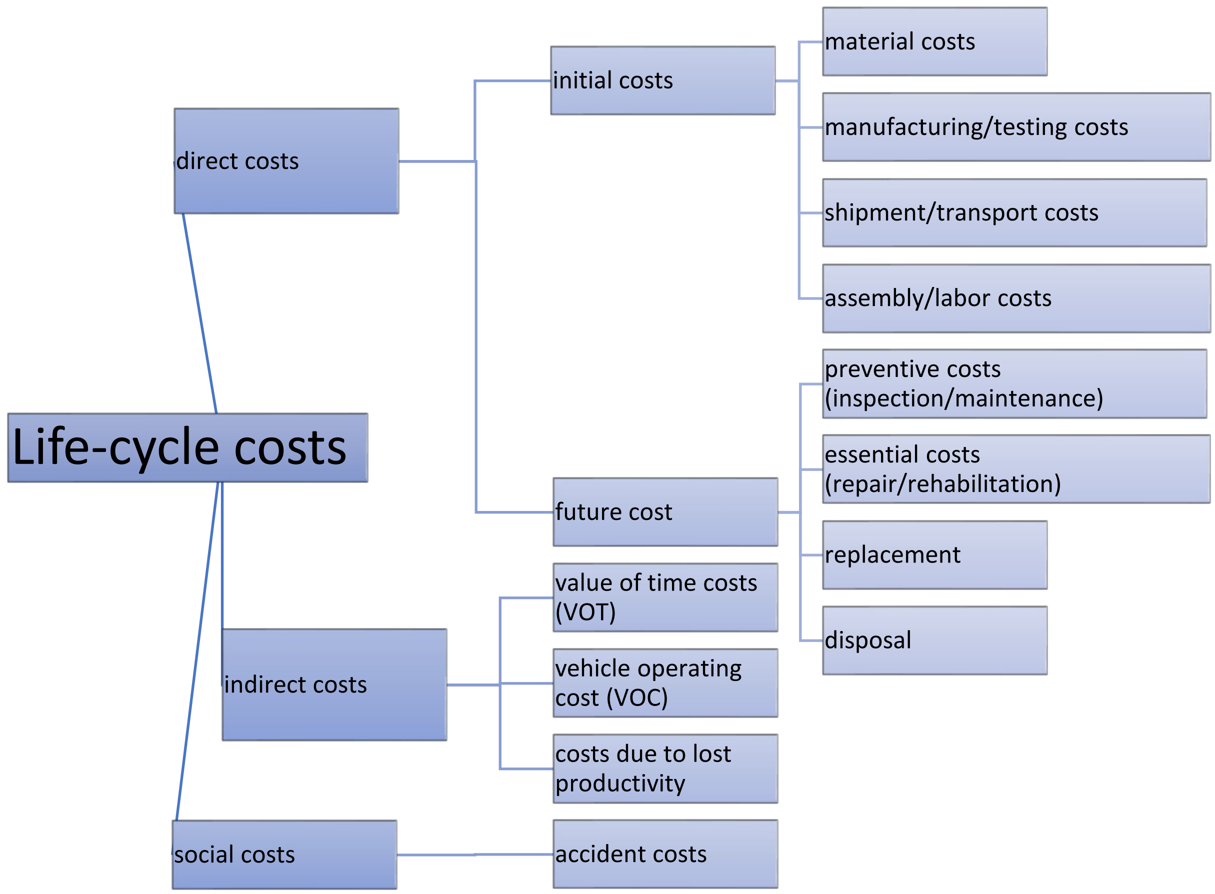

Figure 6 - Life-Cycle cost composition

Direct costs are defined as costs that accumulate before the bridge is used for public or in the future. They are also referred to as agency costs and are paid by the agency that owns the bridge. Costs that appear initially, are costs that occur during the design phase, the manufacturing of the bridge elements as well as during the assembly. This includes material costs, manufacturing and testing costs, transportation costs, costs for assembly and labor costs during the construction phase. Future costs include costs that stem from preventive measures such as maintenance, essential measures such as repair, replacement measures and disposal. The expenses that are carried by the owner are the total costs of acquisition (purchase, construction and installation) added to the costs of inspection, operation, maintenance, repair and disposal. The total agency costs are summed up as follows (Sagemo and Storck 2013):

$$C_{agency} = C_{aquisition} + C_{OM\&R} + C_{disposal} \qquad \text{Eq. 3}$$

where

C_{agency}: expenses of owner

$C_{aquisition}$: cost for material, manufacturing, construction and installation

$C_{OM\&R}$: cost for inspection, maintenance and repair

$C_{disposal}$: cost for disposal of material

User delay, freight mobility, revenue loss, livability during construction, road user exposure and construction personnel exposure costs are categorized as indirect costs (see Figure 6). Indirect costs are associated with costs that are based on reduced traffic capacity or unexpected loss of productivity. These costs should consider delay, vehicle operating costs (VOC) and an increased risk of accidents and are important. User costs can be up to 10 times higher than operation, maintenance & repair (OM&R) costs and therefore they should not be neglected to compile a realistic cost analysis (Thoft-Christensen 2009). User costs are difficult to analyze and therefore they are often neglected. Social costs compile of costs initiated by accidents. User costs compile of indirect costs and social costs.

The costs that are important to calculate user costs can be determined with the following equations. These costs can be calculated either by implying truck and car data separately and using the actual ADT at the construction or non-construction time or if the separated truck/vehicle data is missing, the general ADT can be used. If the latter is the case, the speed limit during construction and non-construction period, the length of the affected roadway and an average time value for drivers are needed. Therefore, travel delay costs C_{TDC} can be calculated with Eq. 4 (Sagemo and Storck 2013) or simplified with Eq. 5.

$$C_{TDC} = T * ADT_t * N_t * (r_T w_T + (1 - r_T) w_p) \qquad \text{Eq. 4}$$

where

T: travel time delay for one vehicle (hr)

ADT_t: average daily traffic on bridge at time t

N_t: number of days of road work at time t

r_T: % of trucks of total ADT

w_T: hourly cost for one truck ($/hrtruck)

w_p: hourly cost for one passenger car ($/hrcar)

$$C_{TDC-Simplified} = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) * ADT * N * w \qquad \text{Eq. 5}$$

where

L: length of affected roadway

S_a: speed during bridge work activity (mph)

S_n: normal traffic speed (mph)

ADT: average daily traffic (veh/day)

N: number of days of road work

w: hourly time value of drivers

The delay of travel time is based on speed reduction, traffic light regulations and traffic diversions. Additionally, vehicle operation costs C_{VOC} shall be determined with Eq. 6 (Sagemo and Storck 2013) or Eq. 7. The calculation considers to fuel, engine oil and maintenance costs.

$$C_{VOC} = ADT_t * N_t * (r_T O_T + (1 - r_T) O_p) \qquad \text{Eq. 6}$$

where

O_T: hourly operating cost for one truck ($/hrtruck)

O_p: hourly operating cost for one passenger car ($/hrcar)

for, further explanation, see Eq. 4

$$C_{VOC-Simplified} = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) * ADT * N * r \qquad \text{Eq. 7}$$

where

r: weighted-average vehicle cost based on average truck-to-auto ratio

for, further explanation, see Eq. 5

Social costs are accrued from traffic accidents that cause health-care and death costs. Accident costs C_{ACC} are calculated with Eq. 8 (Sagemo and Storck 2013) or Eq. 9.

$$C_{ACC} = \sum_{t=0}^{L} ADT_t * N_t * (A_a - A_n) * [(C_F * P_F) + (C_l * P_l)] \frac{1}{(1+r)^t} \qquad \text{Eq. 8}$$

where

A_a: bridge accident rate during work activities

A_n: bridge accident rate during normal conditions

C_F: average cost per fatality for society

P_F: average number of persons killed in bridge-related accidents

C_l: average cost per serious injury accident for society

P_l: average number of persons injured in bridge-related accidents

for, further explanation, see Eq. 4

$$C_{ACC-Simplified} = L * ADT * N * (A_a - A_n) * c_a \qquad \text{Eq. 9}$$

where

A_a: accident rate per vehicle-mile during construction

A_n: normal accident rate per vehicle-mile

c_a: average cost per accident

for, further explanation, see Eq. 5

Vulnerability costs are from collision, risks from overloads, blasts, fires, flood, scour, etc. These costs are often not included in cost analysis due to the difficulty in estimating them (Azizinamini et al. 2013; Saeedi et al. 2013). Social costs are tied to the ADT. The higher the ADT the higher the increase in social costs is (Mara et al. 2014).

3.2. Including environmental impacts in LCC Analysis

During the past decades the concept of sustainability gained in popularity and importance for bridge designs in such a way that bridge engineers are forced to consider environmental impacts during decision-making and design. Therefore, in addition to Greenroads TM and Hunt's, which are not further explained in this work, a new rating system for sustainable bridges was created and conducted in 2013. The rating system was developed with a survey that has helped to define the importance of different criteria (Bianquis 2015). During this step, bridge construction experts rated criteria in order of importance. After elimination of criteria with little importance the Simos' rating system, a simple weighting method, was developed (Table 2). For the future it is important to combine a rating system like Simos' with a conventional LCCA that still neglects environmental costs, here also referred to as third-party costs. Uniting these two methods, the environmental damage which normally comes along with a construction can be minimized. Therefore, an improved overall evaluation can be established.

Table 2 - Rating system criteria by Marzouk, Nouth and El-Said

Criteria	Proposed Credit
Project Requirements (26 credits)	
Life Cycle Cost Analysis	4
Noise Mitigation Plan	3
Waste Management Plan	4
Pavement Management Plan	4
Site Maintenance Plan	3
Potential for Innovations	4
On-site Renewable Energy	4
Environment and Water (21 credits)	
Habitat Restoration	6
Sustainable site selection	7
Respect for historic sites	8
Access and Equity (23 credits)	
Intelligent Transportation Systems	5
Providing a Bridge User Guide	4
Pedestrian/Bicycle Access	5
Transit Access	5
Visual Enhanvements	4
Construction activities (6 credits)	
Equipment Emission Reduction	3
Storage/Seperation areas	4
Materials and Resources (20 credits)	
Pacement reuse	4
Earthwork Balance	5
Recycled Materials Reuse	4
Regional Materials	5
Long-Life Pavement	5
Total	**100**

Even though this includes environmental impacts, carbon emissions are not directly considered during construction, operation and maintenance of a bridge. Additionally, this procedure does not differentiate between bridges and buildings (Bianquis 2015).

Therefore, it is important to create a bridge evaluation regarding the emission of carbon during the whole life span of a bridge.

Throughout an LCA four stages can be determined. At first, a goal and scope need to be defined. This will identify and set up boundaries and objectives. Next, inputs (energy & material) and outputs (goods and activities) of each phase are evaluated throughout the life-cycle inventory analysis (LCI). An LCI includes all energy and material in- and outflow and additionally, includes data calculated from each phase (manufacturing, construction, operation, maintenance and end-of-life). This step is followed by a life-cycle impact assessment (LCIA) which can be subcategorized into classification, characterization, weighting and interpreting outputs. This step helps to understand environmental relevance of all in- and outflows. Lastly, an interpretation of the life-cycle is performed (Ozcoban 2017; Song et al. 2009).

LCA can be performed using four different methods. A full LCA can be obtained by using the cradle-to-grave method which includes the material manufacturing phase including the extraction of raw material and the maintenance and disposal stage, the 'grave'. If only a partial LCA is required, it can be either accomplished with the cradle-to-gate, cradle-to-cradle or gate-to-gate method. Cradle-to-gate is measured from extraction of raw material upon leaving the manufacturers' "gate". The cradle-to-cradle method is a special approach that includes factors that appear in between manufacturing and disposal (Ozcoban 2017).

BridgeLCA investigates the impact of bridges on the environment. For this, the global warming potential (GWP), ozone depletion (ODP), terrestrial acidification (AP), freshwater eutrophication (EP), fossil depletion (FD), human toxicity cancer (HTC), human toxicity non-cancer (HTNC) and ecotoxicity (ET) and more are considered. The first five environmental effects are based on the population in the respective country. Shadow prices are monetizing mentioned environmental effects. These prices are converted from Euro to US dollar prices with the average exchange rate of 2004 and then have been converted to current dollar values using CPI. Resulting shadow prices are presented in Table 3.

Table 3 - Environmental effect categories and shadow prices (Bosman 2015)

Environmental effect category	Unit	Shadow price ($/lb equivalent)
Abiotic depletion elements (ADP)	$/Sb eq	0.60
Abiotic depletion fossil (ADP)	$/Sb eq	0.60
Global warming potential (GWP)	$/CO2 eq	0.18
Ozone depletion potential (ODP)	$/CFK-11 eq	111.4
Photochemical ozone formation potential (POCP)	$/C2H2 eq	7.43
Acidification potential (AP)	$/SO2 eq	14.86
Eutrofication potential (EP)	$/PO4 eq	33.42
Human toxicity potential (HTP)	$/1.4-DCB eq	0.33
Freshwater aquatic ecotoxicity potential (FAETP)	$/1.4-DCB eq	0.11
Marine aquatic ecotoxicity potential (MAETP)	$/1.4-DCB eq	0.0004
Terrestric ecotoxicity potential (TETP)	$/1.4-DCB eq	0.22

The environmental effects per impact category can be calculated with

$$EE_i = \sum_{j=n}^{m} EE_{i,j} * Mq_j \qquad \text{Eq. 10}$$

where,

EE_i: environmental effects for impact category i expressed in equivalents

$EE_{i,j}$: environmental effect for impact category i per kg of material j

Mq_j: material quantity per functional unit for material j

j: different materials n until m

Therefore, the total environmental costs can be determined with the following equation.

$$SC = \sum_{i=n}^{m} EE_i * SP_i \qquad \text{Eq. 11}$$

where,

SC: social costs

EE_i: environmental effects for impact category i

SP_i: shadow price for environmental category i (Table 4)

i: environmental impact category

for, further explanation, see Eq. 11

Embodied energy is consumed by the material during the production process and during maintenance throughout the whole life-cycle. On the contrary carbon is emitted throughout the whole life-cycle. The amount of energy that is consumed by different materials is shown in the diagram in Figure 7. Usually, FRP bridge decks use glass fibers due to its relatively low energy consumption. The diagram shows that the energy consumption of concrete is less than the one of GFRP, however, the quantity of a GFRP bridge deck is smaller than for a reinforced concrete bridge deck. The actual exemplary consumption for a 40 ft. road bridge is shown in Figure 8. Exact embodied energy values can be taken from Table 4.

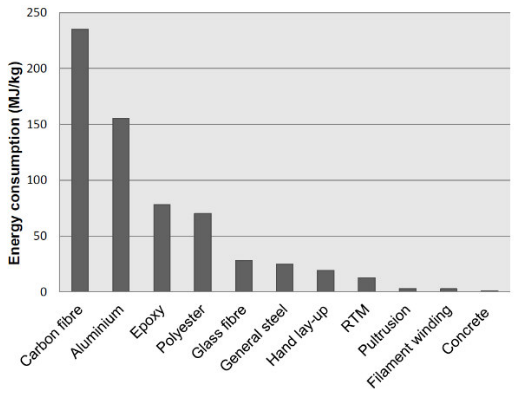

Figure 7 - Energy consumption during production/manufacturing process (Mara et al. 2014)

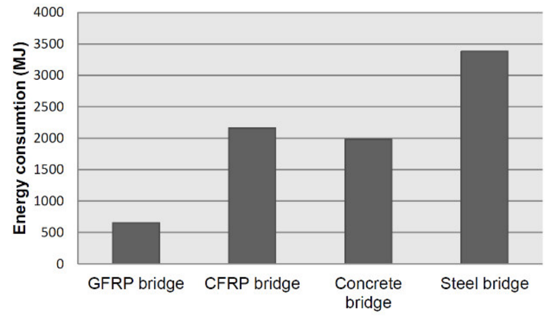

Figure 8 - Consumption comparison of a 40 ft road bridge (Mara et al. 2014)

Table 4 - Unit amount of embodied energy (Zhang et al. 2011)

Heading		Unit amount of Embodied Energy MJ/lb
Materials	Prefabricated prestressed concrete	4.409
	Concrete (general)	2.094
	Reinforced steel	54.234
	Asphalt	5.313
	GFRP	220.462
	Epoxy resin	307.104

However, every phase that introduces embodied energy will also release carbon. Therefore, carbon emissions should also be considered in an environmental analysis. Carbon emission can be found throughout every life-cycle stage. It is proportional to the mass of used material. The specific amounts of carbon emission for several materials are taken from Mara and Zhang et. al and are presented in Table 5.

Table 5 - Unit amount of carbon emission amounts (Mara et al. 2014; Zhang et al. 2011)

Heading		Unit	Unit amount of CO_2 emissions
Materials	Prefabricated prestressed concrete	$lbCO_2/lb$	0.215
	Concrete (general)		0.130
	Reinforcment steel		1.710
	Asphalt		0.140
	FRP		5.000
	GFRP		8.100
	Aggregate		0.005
	Epoxy resin		5.910
	Polymer concrete		1.180
	Insulation		2.500
	Paint	$lbCO_2/ft^2$	0.107
Transportation	Road	$lbCO_2/t*mi$	0.379
	Water		0.053
Vehicle	General	gCO_2/mi	1.064

CHAPTER 4

METHODS

4.1. Methods for LCCA Evaluation

LCCA can be either performed in a simplified approach, which is also known as deterministic analysis, and can be even done with Microsoft Excel. A more advanced approach could also be taken which involves attempting to decrease the uncertainty of future consequences, i.e. sensitivity analysis, risk analysis with Monte Carlo simulation. While the deterministic approach uses fixed assumed and estimated values, the sensitivity approach considers the significance and uncertainty of previously made assumptions for the deterministic approach. A risk analysis takes over when the sensitivity approach fails. Risk analysis is a probabilistic approach that is applied on construction cost, repair cost and timing uncertainties.

4.1.1. Deterministic Approach

To complete a simplified but full LCCA a deterministic approach can be done. It consists of 5 steps which need to be accomplished as listed below (Azizinamini et al. 2013).

1. Establishment of design alternatives
2. Determination of activity timing
3. Estimation of cost
4. Computation of LCC

5. Analysis of results

A minimum of at least one additional design alternative needs to be considered for comparison purposes of financial feasibility of the considered design. It is also important to identify the upkeep activities that are essential throughout the service life of the bridge. The establishment of design alternatives including its determined activities is followed by the determination of activity timing.

Activity timing needs to be accomplished as part of the identification process. The duration and frequency of every activity, e.g. maintenance, needs to be determined due to expected wear or after a specified time period. Usually, decks need more frequent maintenance and need to be replaced in shorter time-periods than their substructure for example. In default of existing data, the opinion of experts can be taken into consideration or realistic assumptions can be made.

Besides the determination of initial costs, future costs and optionally indirect costs, need to be added to the previously determined activities.

In the next step the costs listed for each activity are stated in actual dollar values. Therefore, future cash flow needs to be converted into present-day dollar values or discounted cash flow, also referred to as current dollar values, using a discount factor. For LCCA a real discount rate is used while for life-cycle cost benefit analysis a nominal discount rate is used for the calculation. A life-cycle cost benefit analysis, which will not be addressed in more detail in this thesis, includes direct and indirect costs and is meaningless with high discount rates. A real discount rate does not include the effects of inflation but considers the financial risk and the time value of money. It is used for future costs that are estimated with the present-day dollar value. Especially for long-term investments it is recommended to use real discount rates. In contrast, inflation, financial risk and the time value of money are considered in the nominal discount rate. The nominal discount rate can be calculated with the following equation (FHWA 2013):

$$Nominal\ discount\ rate = (1 + real\ discount\ rate)x(1 + inflation\ rate) - 1 \quad \text{Eq. 12}$$

Since inflation is complicated to predict for the long run, the effect of inflation is often neglected for the calculation. The discount factor can be calculated with the discount rate r and the time t in years as followed:

$$f(r,t) = \frac{1}{(1+r)^t} \quad \text{Eq. 13}$$

The discounted cash flow (DCF) can be determined by multiplying the discount factor with the amount of cash flow C (costs) in US Dollar:

$$DCF = \frac{c_t}{(1+r)^t} \quad \text{Eq. 14}$$

The net present value (NPV) is the sum of initial costs and all discounted cash flows that happen in the future factoring in the effect of inflation. The NPV is needed to convert present and future costs into a common metric. It is important to mention that the NPV method can only be used appropriately when the alternatives to be examined are the same (Azizinamini et al. 2013; Sagemo and Storck 2013).

$$NPV = \mathrm{IC} + \sum_{n=0}^{L} \frac{C_t}{(1+r)^t} \quad \text{Eq. 15}$$

A higher discount rate is primarily used by private investors when risks of investing are high and future costs are not rated as important. Therefore, LCCA is ineffective using high discount rates. Public authorities tend to use a lower discount rate. Low discount rates are used when future costs take an immense part in design decision making.

Economic, social and political factors have influence on discount rates. Private investors typically use a real discount rate of 2 to 14% whereas public authorities use a real discount rate of 2 to 5% (Thoft-Christensen 2009). Due to social, economic and political factors discount rates and therefore, the rates used by various countries are different. While many countries use an unrealistic high discount rate of 6%, a discount rate of 2 to 3% is more likely to be used in the United States (Setunge et al. 2002). In Sweden however, a discount rate of 2.9% is used. For the best and most realistic outcome it is recommended to include agency as well as user costs. This is a highly complex step and is therefore performed computationally. Regarding the significance and the uncertainty of parameters a sensitivity approach and stochastic approach should be done. These approaches are explained in the following sections. The type of analysis chosen to be carried out depends on the needs and requirements. A deterministic LCC analysis can be performed using software with an included tool to run NPV calculations. Alternatively, calculations can be done manually with Microsoft Excel if risks and uncertainties are neglected (e.g. Appendix A).

To finalize the LCCA, the results of the different design alternatives are compared, and the best overall long-term benefit option needs to be determined. Results of the comparison of the alternatives can be shown by using visual designs such as graphs or tables.

4.1.2. Sensitivity Approach

A sensitivity analysis is a computational technique that considers the significance and uncertainty in previously made assumptions. It explores the degree to which LCC depend on initial assumptions. These assumptions relate to the time period, discount rate, traffic growth, speeds, capital costs and accident predictions. The sensitivity approach can be separated into two independent steps. At first, model variables that show significant influence on the model outcome need to be identified. Secondly, points that alter consideration ranking are to be determined. Therefore, minimum and maximum values need to be set by engineers with a confidence interval of 95%. This describes the certainty of 95% by an engineer that the value lies between the set minimum and maximum (Christensen et al. 2005). Austroads, which is the main organization of Australasian road transport and traffic agencies, suggests different parameters that can be taken into consideration by engineers. These provided ranges are shown in Table 6 and are also applicable in the United States. Therefore, capital costs can be taken into consideration with a minimum value of -10% and a maximum value of 10% of the estimate (Bosman 2015; Department of Transport and Main Roads 2011). This can be applied and carried on throughout the parameters considered to be sensitive in cost estimation.

Table 6 - Input variables and their uncertainty distribution

Variable type	Variable	Type of distribution	Deviation from mean value (minimium to maximum values)
Inflation Rate		Triangular	-10 % to +10 %
Discount Rate		Triangular	-10 % to +10 %
Construction Unit Cost (CUC)	GFRP deck, Concrete deck, Asphalt, Wearing Surface	Triangular	-10 % to +10 %
Activity Unit Cost (AUC)	Replace asphalt, Replace wearing surface, Asphalt maintenance, Concrete repair	Triangular	-10 % to +10 %
Construction Element Quantity (Cq)	Concrete deck, GFRP deck, Asphalt, Wearing surface	Triangular	-10 % to +10 %
Quantity of units for activities (Aq)	Replace Asphalt, Replace wearing surface, Asphalt maintenance, Concrete repair	Triangular	-10 % to +10 %
New technology costs	unassigned object risks, engineering costs, material testing costs	Triangular	-25 % to +25 %
Traffic speeds		Triangular	-25 % to +25 %
Traffic growth rate		Triangular	-2 % to +2 %
Activity Duartion (N)	days & labor-hours	Triangular	-50 % to +50 %

The sensitivity analysis provides an insight into the variability of model results across a range of variable estimates while it has three clear disadvantages. It fails in identifying a dominant alternative as well as it is only able to analyze ranges of single variables but cannot determine the outcome when these ranges of different variables act together at the same time. Additionally, a probabilistic distribution is absent. A likelihood of particularly occurring values is not explored.

4.1.3. Risk analysis

This approach takes over when a sensitivity approach fails. It improves the shortcomings of the sensitivity analysis that are listed in the previous section. To perform a stochastic analysis the probabilistic density and distribution function of the model variables are needed. Therefore, the engineer needs to determine the possible cases that can occur. Risks can be known knowns, known unknowns and unknown unknowns. Especially for the last two cases a computational risk analysis software is needed. For a probabilistic assessment either exact or random sampling methods can be used. Table 5 shows input variables and the method of how to initialize them (Setunge et al. 2002). Due to its complexity it is done with a computational software (i.e. BridgeLCC 2.0, BLCCA, etc.) which generates a cumulative distribution of the model outcomes (Hawk 2003). Therefore, a cumulative distribution represents a model outcome under combined influence of all model variables acting together and can be understood as a basis for the comparison of different options (Christensen et al. 2005).

Table 7 - LCC Analysis Input Variables (Setunge et al. 2002)

Analysis Components	Input variables	Sources
Initial & Future costs	Preliminary engineering	Estimation
Timing of costs	Construction	Estimation
	Maintenance	Assumption
	Bridge performance	Projection
User costs	Current traffic	Estimation
	Future Traffic	Projection
	Hourly demand	Estimation
	Vehicle distribution	Estimation
	Dollar value of delay time	Assumption
	Work zone configuration	Assumption
	Work zone hours of operation	Assumption
	Work zone duration	Assumption
	Work zone activity years	Projection
	Crash rates	Estimation
	Crash cost rates	Assumption
NPV	Discount rate	Assumption

4.1.4. Monte Carlo simulation

The Monte Carlo simulation is a numerical method that enables professionals to account for risk in a quantitative analysis and decision making. Therefore, the simulation estimates the probability distribution of parameters depending on several stochastic variables (Hawk 2003). This method is used in several fields, i.e. in finance, project management, energy, research, development, etc. During the analysis, sampled values of independent variables are randomly repeated. Subsequently, it allows the decision maker to detect which exact actions are possibly followed by an exact reaction.

The number of recalculations during the simulation depends on the number of uncertainties and the parameters' ranges. A completed Monte Carlo simulation can easily consist of tens of thousands of recalculations. A software example to conduct a Monte Carlo simulation is @RISK by the company Palisade.

4.2. Computational Software

Software especially help to obtain a full LCCA when risks and cost variations possibly occur. Software that are used to obtain risk impacts and conduct a Monte Carlo simulation should offer an intuitive interface, a detailed and well devised probability distribution and a close collaboration between analysts and decision makers. Additionally, software should run thousands of cases for an examination of the likelihood that an extreme event occurs. Furthermore, identifying uncertain variables and clearly displaying the results are substantial requirements (Sugiyama 2008). A selection of different types of software are mentioned in the following paragraphs with their features.

BridgeLCC 2.0 is a user-friendly software developed by the National Institute of Standards and Technology (NIST) and can be downloaded from *nist.gov* at no cost. NIST also offers a User Manual that guides the user step-by-step through a whole analysis example. The software assesses cost-effectiveness of conventional as well as alternative materials and can therefore also be used on FRP bridge designs. BridgeLCC 2.0 uses LCC methodology that is based on ASTM standard E917 and cost classification which are developed by NIST. The software can run in two modes between which the users can switch back and forth without data loss. The basic mode is executed with best-guess values of amounts and timings of costs without uncertainties. The first step of this mode is to enter all values and compute an LCCA. Then, the second step executes a sensitivity analysis and states how changes of individual parameters affect the overall LCC. The advanced mode accounts for uncertainties for amounts and timings of costs. There are four possible probability distribution types from which are assigned to every parameter, that is entered in the software. These distribution probability types are uniform, normal, triangular or lognormal. Needed values for the different probability distribution types are:

Table 8 - Probability distribution types and needed values

Probability Distribution Type	Values to be provided
Uniform	minimum, maximum
Normal	mean standard deviation
Triangular	minimum, most likely, maximum
Lognormal	mean standard deviation

The software allows the user to assign probability distributions to all unit costs, quantities, year of event, inflation and real discount rate. Probability distributions help to determine the effect of fluctuation on the project cost outcome throughout the design life. Entering all the distribution possibilities is followed by a Monte Carlo simulation that shows how uncertainties in individual costs create uncertainty in overall LCC effectiveness. Additionally, BridgeLCC 2.0 offers several support tools. Especially of interest for FRP Bridges is the so called WorkZone window. It allows an estimation of user costs per day that are caused by costs related to the time delay, the car deterioration from extra driving distances caused by detours and the additional gas needed for these extra miles.

To start off an evaluation for a new project a window New Project Wizard appears in BridgeLCC 2.0. To get to the next step, the name of the project, the name and number of alternatives is required. The maximum number of alternatives than can be examined is limited to five. Additionally, the base year, the time period for the evaluation and the interest rates including inflation rate and discount rate is required. BridgeLCC 2.0 proposes an inflation rate of 1.80% and a real discount rate of 3.20%. The nominal discount rate of 5.06% is the convergence of these rates. A computation of bridge costs in the future are calculated with the inflation rate while the real discount rate computes these future costs into present values. For the full LCCA on a bridge in Rhode Island in chapter 5 the software BridgeLCC 2.0 is used. Alternative software that can be used to perform a full LCCA are @RISK by Palisade, Crystal Ball by Oracle and Risk Solver/Premium Solver Platform by Frontline Systems.

BridgeLCA is an Excel-based software that performs LCAs on bridges. It is part of the Scandinavian ETSI project, that tries to optimize bridge life-cycles considering all aspects during the whole bridge life. The analysis can be run in a simplified BridgeLCA or in an advanced version (see Figure 9). While the simplified mode only takes initial construction work into account, the latter performs the analysis through the whole life of a bridge. BridgeLCA investigates the impact of bridges on the environment. For this, the global warming potential (GWP), ozone depletion (ODP), terrestrial acidification (AP), freshwater eutrophication (EP), fossil depletion (FD), human toxicity cancer (HTC), human toxicity non-cancer (HTNC) and ecotoxicity (ET) are considered. The first five potentials are based on the population in the respective country (Mara et al. n.d.). To obtain a sensitivity analysis all these potentials can be added with a 10% increase.

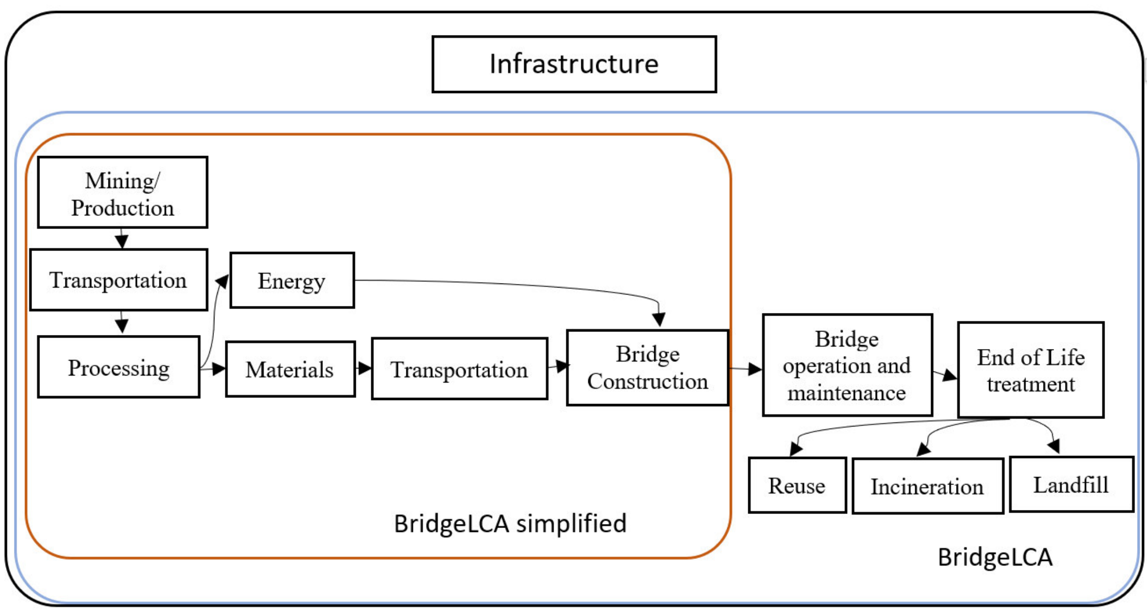

Figure 9 - Comparison BridgeLCA and BridgeLCA simplified (Salokangas 2009)

CHAPTER 5

ANALYSIS & RESULTS

The following analysis is performed on the state owned Canonchet Bridge (Bridge No. 056701), built in 1969, which carries Woodville Alton Road in Hopkinton, RI over Interstate I-95 South and North. In the Bridge Inspection Report of December 15, 2015, the bridge deck, superstructure and substructure are rated fair. Canonchet Bridge needs rehabilitation due to structural deterioration and inadequate strength (RIDOT et al. 2017).

Figure 10 - a) Location in RI (Google Maps); b) Top view I-95/Woodville Alton Rd (Intermap)

Figure 11 - Canonchet Bridge on I-95 northbound (Google Maps 2017)

The ADT on Canonchet Bridge is expected to increase due to planned installment of toll stations on I-95 in Hopkinton, RI and Exeter, RI for heavy vehicles (class 8 to 13 – four or less axle single trailer up to seven or more axle, multi-trailer). The consequence is that vehicles will circumvent around the toll stations, while exiting I-95 North at Exit 2, crossing I-95 via Canonchet Bridge towards Route 3 (see map in Appendix B).

The analysis conducted, examines the LCC of a pultruded GFRP deck and a conventional reinforced concrete deck. To perform this analysis assumptions for several input variables need to be made (also see Table 6) that are listed below and are common in both analysis cases.

- Service life of the bridge is 75 years (RIDOT), so the LCC study period is set at 75 years
- The inflation rate is 1.8%, the real discount rate to compute the present values of future costs is 3.2% and therefore, the nominal discount rate is 5.06% (recommended by BridgeLCC 2.0 and NIST)
- Length of roadway affected by bridge construction: 1 mile each for I-95 and Woodville Alton Road

- Average Daily Traffic (ADT): 2,082 (Canonchet Bridge 2016 – no tolling on I-95; NBI)
- ADT: 48,287 (I-95; NBI)
- Expected ADT on Canonchet Bridge with toll on I-95 in 2036: 2,499 (NBI)
- Normal driving speed on I-95: 65 mph
- Normal driving speed on Woodville Alton Road: 25 mph
- Average driving speed on I-95 during bridge construction: 55 mph
- Average driving speed on Woodville Alton Road during bridge work: remains 25 mph
- Normal accident rate (per million-vehicle-miles): 1.9
- Accident rate in road work areas (per million-vehicle-miles): 2.4 (Ozturk 2013)
- Hourly value to drivers due to delay: $27.54/hr
- Hourly VOC: $23.34/hr ((Mara et al. 2014); Adjusted 2018 with CPI)
- Average cost per accident: $173,720 (CALTRANS 1995; Adjusted 2018 with CPI)

For the calculation it is important to know the accident rate and the length of the roadway section, that is affected by construction, OM&R and disposal. These parameters need to be observed before starting the analysis. The work zone length on I-95 underneath Canonchet Bridge comes up to 50 feet and up to 600 feet of work zone are needed on Woodville Alton Road (RIDOT 2017). The road stretch that is affected by bridge works is estimated to be one mile long during construction and half mile long during operation, maintenance and repair (OM&R) works on I-95 as well as on Woodville Alton Road. The ADT on Woodville Alton Road is at 2,082 (FHWA 2018). Therefore, the crash rate can be calculated with the following equation (FHWA 2011).

$$R = \frac{C * 1{,}000{,}000}{ADT * 365 * N * L} \qquad \text{Eq. 16}$$

R: crash rate in million vehicle miles travelled

C: total number of crashes in section

ADT: average daily traffic during study period

N: Number of years of data

L: length of affected roadway in miles

In many states the crash rate per million vehicle miles travelled is assumed to be between 2 and 3 on rural two-lane roads (Oregon State University n.d.). Crash rates increase by 24.4% under work zone conditions (Ozturk 2013). Therefore, 1.9 and 2.4 were chosen for this analysis as normal crash rate and crash rate during constructions, respectively. The average accident cost data emanates from (Ehlen and Marshall 1996) and was adjusted to the present dollar value using the consumer price index (CPI).

Travel delay costs can be obtained by computing known data in Eq. 5. The hourly time value of drivers emanates from an average truck-to-auto ratio. An illustration of hourly travel time costs by vehicle class can be seen in Figure 12. It is assumed that one in 10 vehicles crossing Canonchet Bridge is a truck. The hourly travel value of $27.54/hr which is used for this analysis results from this assumption. Alternatively, an hourly travel time value of $28.97/hr is recommended by the Washington State Department of Transportation (WSDOT 2014).

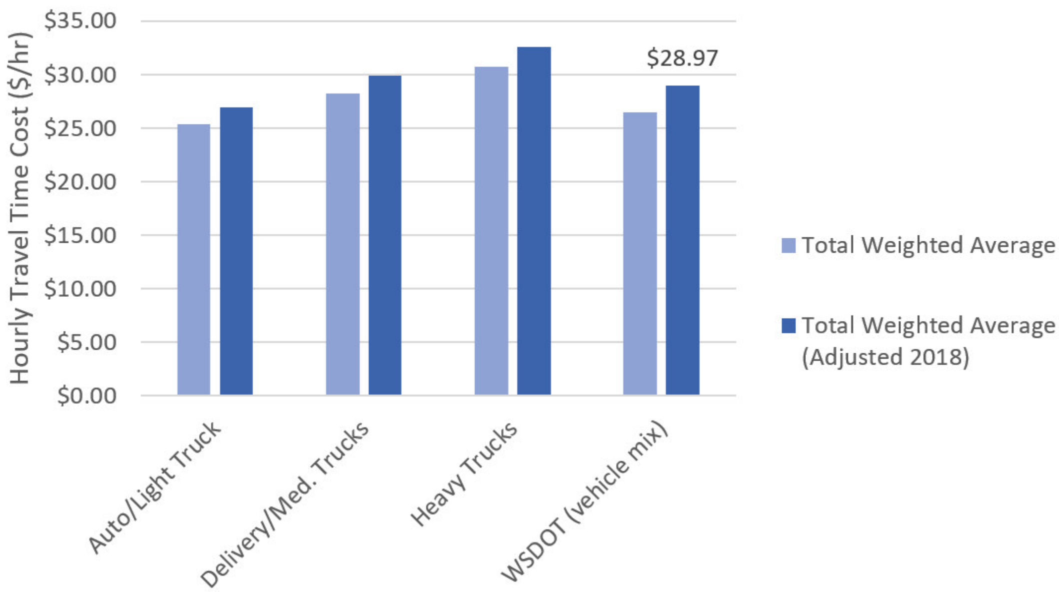

Figure 12 - Hourly Travel Time Value by Vehicle Class (Denise 2016; WSDOT 2014)

The majority of costs used for this analysis are based on a cost listing of a bridge in Brunswick County, North Carolina that carries a two-lane overpass of NC130 over the four lane US17 (Ehlen and Marshall 1996). The bridge deck in North Carolina is about 35% larger than the bridge deck used for this analysis. Therefore, costs were adjusted not only to the size of the bridge but also to the current dollar values using CPI and the improved manufacturing and design process for FRP.

In the following two subchapters the parameters used for the analysis are stated and categorized by timing and cost bearer. Each alternative starts off with initial construction costs, continues with OM&R costs and rounds off with disposal costs. Each of these categories are segmented into levels of costs by its bearer that are agency costs and user costs. Third-party costs are not included in this analysis. A specified cost-listing can be found in Appendix C and D. For these two alternatives, the same bridge dimensions were used. The bridge is 142 feet long with a total deck area of 9601 ft^2.

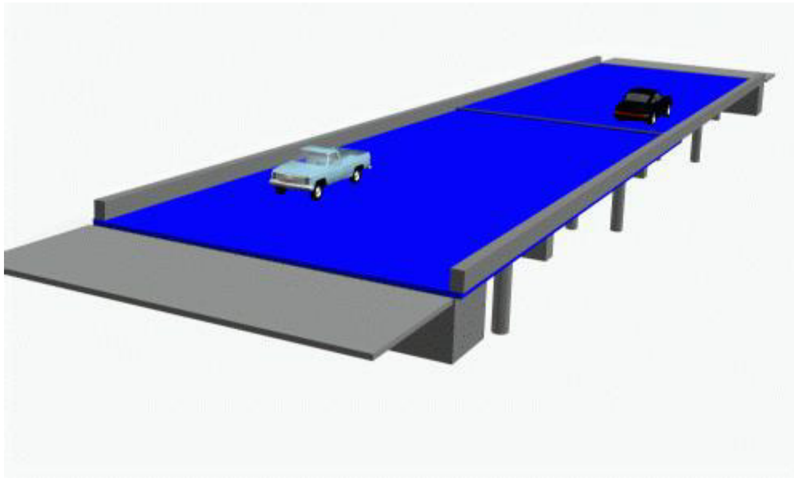

Figure 13 - Computational drawing of the bridge

5.1. FRP Bridge Deck

The material used in this alternative is fiberglass and vinyl-ester. Fiberglass was chosen due to the lower material cost compared to carbon. It is a material that has a very low weight. Something notably interesting in this case is the low energy consumption of glass fibers. At first, glass fibers seem to be the material with the highest embodied energy but when considering the small mass of used material for a construction, it shows how small the total amount of embodied energy is compared to conventional materials. The deck exhibits a thickness of 7.9 in (20 cm) and is shown in Figure 14. A three-rail metal guard barrier is installed along the sides and the middle of the deck. All listed costs are given at current U.S. dollar value. The total costs of this alternative without taking sensitivities of amounts and costs into account is $704,893. Comparison pie charts of costs for both alternatives can be found in Appendix E.

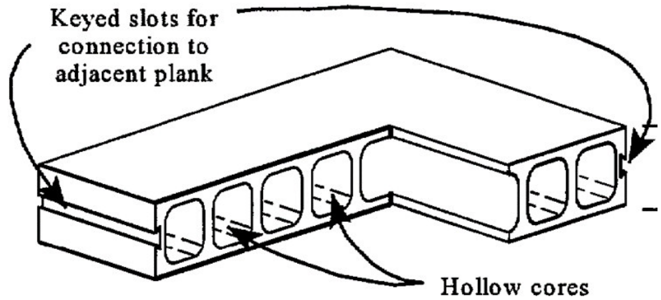

Figure 14 - Pultruded-Plank FRP Deck (Ehlen and Marshall 1996)

5.1.1. Initial Construction Costs

Costs for fabrication including material costs had a value of $23/ft^2 in 1996. Adjusted to the current dollar value, it now costs $37.5/ft^2. It is assumed that due to improvement of manufacturing process as well as the gained knowledge and experience using FRP as a construction material, the price has dropped by 10%. Therefore, $33.75/ft^2 was used as costs for the fabrication process including material costs. Shipping costs were adjusted to the present value dollar and the decreased area of the deck so that a lump sum of $30,750 was used for the analysis. A 5% beam surcharge is added with $8,248 which also was adjusted to the year and the deck size. Bearing installation is taken as a lump sum of $6,110.50 and the on-site installation costs $8.15/ft^2. Since FRP still counts as a relatively new construction material for which design codes still do not exist, this analysis includes new-technology costs such as laboratory tests, costs for meetings with fabricators, field engineers and academic design consultant and pre-design NTM project formulation.

During the period of construction, there will be a lane closure on I-95 in both directions and Woodville Alton Road will be completely closed. The duration of installation of the pre-fabricated deck is predicted to take 5 days. Due to the influence of the construction on the traffic flow, as well as the increased risk of accidents the total amount of user costs comes up to \$56,237 during the phase of construction while the total initial costs including agency and user costs sums up to \$633,118.

5.1.2. Operation, Maintenance and Repair Costs

Since FRP counts as a new construction material, frequent monitoring is essential during the first few years. Therefore, there is an inspection planned every month throughout the first year of operation. It is assumed that a monthly inspection throughout the first year would not be needed due to advanced usage of FRP in the industry. The frequency between inspections from the second to the fourth year is six months and starting in the fifth year there will be biennial inspections held according to NBI. Inspections are assumed to be performed in only one day with two workers. The FRP deck is replaced rather than repaired and therefore, replacement is considered every 50 years according to life expectancy data (75 years for pedestrian FRP bridge decks) (Steere Engineering 2017). The replacement of the deck costs \$5.24/ft^2 and the repatching of the wearing surface costs \$3.26/ft^2. The deck needs repatching every 25 years starting in year 25. The development of a non-destructive evaluation plan could possibly be provided every 25 years by the manufacturer and costs \$81.47/labor-hour at 40 labor-hours.

The effect of OM&R on user costs differ from the previous chapter. During maintenance there is no change in speed limit or lane closure, hence only accident costs appear. For the renewal of the deck one lane will be closed on Woodville Alton Road, but all lanes on I-95 remain open. Though, the speed limit is reduced from 65 mph to

55 mph in both directions on I-95. Therefore, users face costs of $2,792 during OM&R while the total cost of OM&R, that includes agency and user cost, is $58,874.

5.1.3. Disposal Costs

Disposal costs were simplified in only four cost items. Disposal of the deck and the dump fee is born by the agency. The deck disposal costs $24.44/labor-hour and takes about 150 labor-hours. A dump fee was taken from Ehlen and Marshall and was adjusted to the material volume and the current dollar value and is $11,610. Five days are needed for the disposal of the deck which costs the user $11,416. Disposing the bridge deck costs $12,901.

A list with LCC that were evaluated with the costs that were used in the analysis and were described in sections 5.1.1 through 5.1.3 can be found in Appendix C.

5.2. RC Bridge Deck

The reinforced concrete deck calls for a 11.8 in (30 cm) concrete slab poured over prestressed beams that run longitudinally and transverse to the traffic. Costs that apply during the life-cycle of this alternative with reinforced concrete are explained in the sections 5.2.1, 5.2.2 and 0. The total costs of this alternative without taking sensitivities of unit amounts and unit costs into account is $704,661.

5.2.1. Initial Construction Costs

The cost for construction of the RC deck was extracted from Ehlen and Marshall. The paper states the bridge deck construction cost at $15/ft^2 and adjusted using CPI its current dollar value is $24.44/ft^2$. Since reinforced concrete is a well-established and researched material, there is no change in cost due to expected technology progress. The construction takes approximately 21 days which leads to user costs of $236,194. These high costs result from the long construction period and the full road closure of Woodville Alton Road as well as lane closures in each direction on I-95 for the full construction period of Canonchet Bridge. Therefore, the sum of initial costs is $470,843.

5.2.2. Operation, Maintenance and Repair Costs

The inspection costs and period does not differ from the FRP alternative. Therefore, the deck is inspected biennial and every inspection takes one day, and 2 workers are needed for it. Inspections do not affect I-95 in any way. There are no additional VOCs or driver delay costs since the speed limit on Woodville Alton Road is not reduced during inspection. However, there is an increased risk of accidents due to driver distraction. It is assumed that every 25 years 5% of the deck needs to be resurfaced starting in year 15. Every 15 years 2.5% of the deck need to be resurfaced starting in year 10. Agency and user costs for resurfacing sum up to $7,819 and $3,910, respectively. Due to the small resurfacing areas, these surface corrections can be done during night hours, which allows the neglection of user costs in the analysis. The whole deck needs to be resurfaced every 25 years starting in year 25. The unit costs for resurfacing the whole deck are $16.29/ft^2$. The total of OM&R is $166,080.

5.2.3. Disposal Costs

The disposal of the deck costs \$24.44/ft^2. Due to the deck disposal one lane per direction on I-95 and all of Woodville Alton Road are closed. One mile of traffic is affected by these traffic flow changes. The disposal takes about 10 days. Additionally, on I-95 the speed limit is reduced from 65 mph to 55 mph. The user costs of \$44,929 result from these factors. Appendix D lists up LCC that are described and applied to the analysis in sections 5.2.1 through 5.2.3. A list of all costs can be found in Table 9 which shows the costs organized in groups as cost bearer, time of cost and components.

Table 9 - Categorized total costs of both alternatives

	Name	Base Case	Alternative #1
	Total Life-Cycle Cost	**$ 704,893**	**$ 704,661**
By Cost Bearer:	Agency Costs	$ 634,448	$ 420,231
	User Costs	$ 70,445	$ 284,429
	Third-Party Costs	$ 0	$ 0
By Cost Timing:	Initial Construction Costs	$ 633,118	$ 470,843
	OM&R Costs	$ 58,874	$ 166,080
	Disposal Costs	$ 12,901	$ 67,738
By Cost Component:	Elemental Costs	$ 586,114	$ 704,661
	Non-elemental Costs	$ 0	$ 0
	New-Technology Introduction	$ 118,779	$ 0

5.3. Sensitivity Analysis

Due to the many approximations involved in the analysis it is important to perform a sensitivity analysis to examine the influence of the approximations on the results. For all cost items and amounts, a distribution is applied to the analysis. Table 6 in section 4.1.2 lists the distribution types and the deviation from the mean value that were used to receive sensitivity results. An excerpt of the correlation of parameters used for the analysis of Canonchet Bridge is shown in Figure 15. Workzone speed limits of alternative 1, RC bridge deck, on I-95 show the highest negative correlation with -14.44% for an increase of a variable of 10%. A negative correlation indicates an increase of total costs if the input value is decreased. In case of positive correlation, increased total costs result from increased input values. For the base case, the highest influence can be read for the factory costs with a correlation of positive 4.60%. Hence, total costs increase by 4.60% when factory costs or factory quantity increase by 10%. In Appendix E all factors and their effects. similar plots for the alternatives are shown. Any input with an effect of less than 1% is considered ineffective and does not have a significant effect on the final output (Hatami and Morcous 2013).

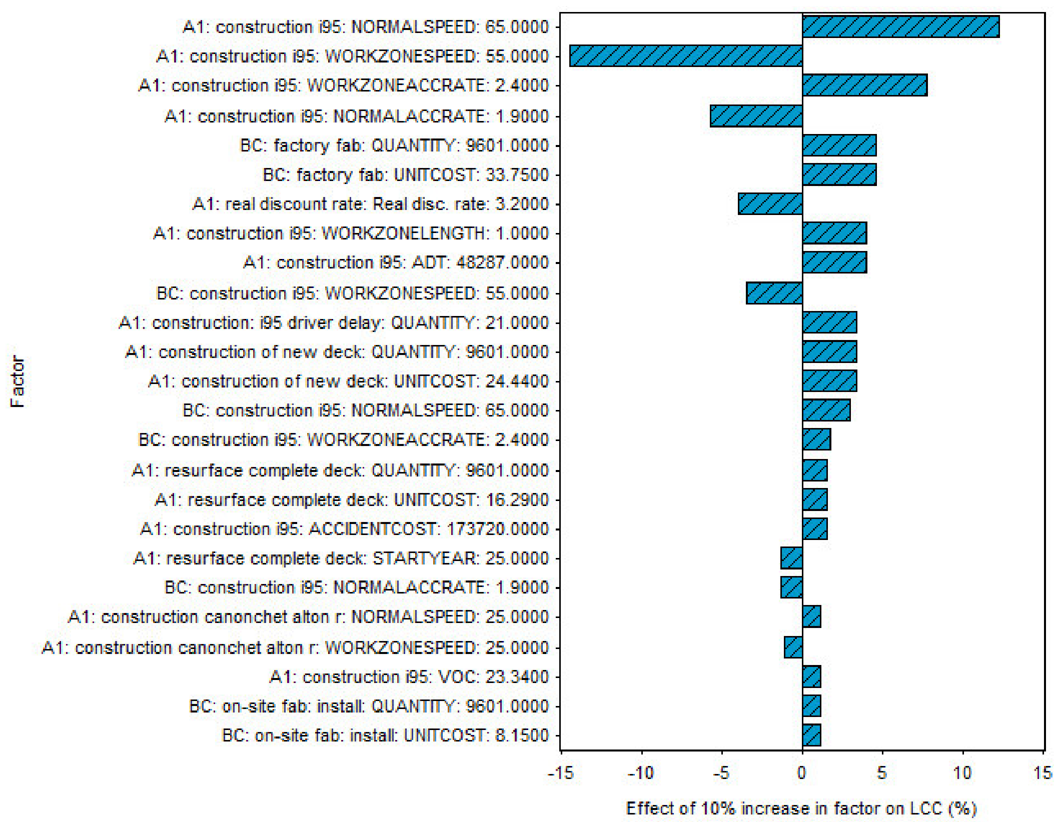

Figure 15 - BridgeLCC 2.0 Sensitivity analysis top 25 results by effect

The influence of the discount rate used for the analysis on the outcome is visualized in Appendix I. The intersection point can be read roughly at 3.20%. At this discount rate the costs of both alternatives are the same if no other parameter changes. The smaller the discount rate gets, the more economical is the base case with an FRP bridge deck.

5.4. Risk Analysis

Deterministic analysis shows that both alternatives can be constructed with about the same costs when costs that appear throughout the whole life-cycle are considered. Figure 16 shows the cumulative probability curve for 3,000 samples. The graph was developed using the distribution of LCC. It plots a lower LCC for the FRP deck than for the RC deck alternative. Another way, to read this graph is that, at a 90% cumulative probability the FRP deck can be constructed for about $665,517 while the RC deck could be constructed for a bit more than $785,803 at the same cumulative probability. The cumulative probability, that the RC bridge deck can be constructed at $665,517, is approximately 15%.

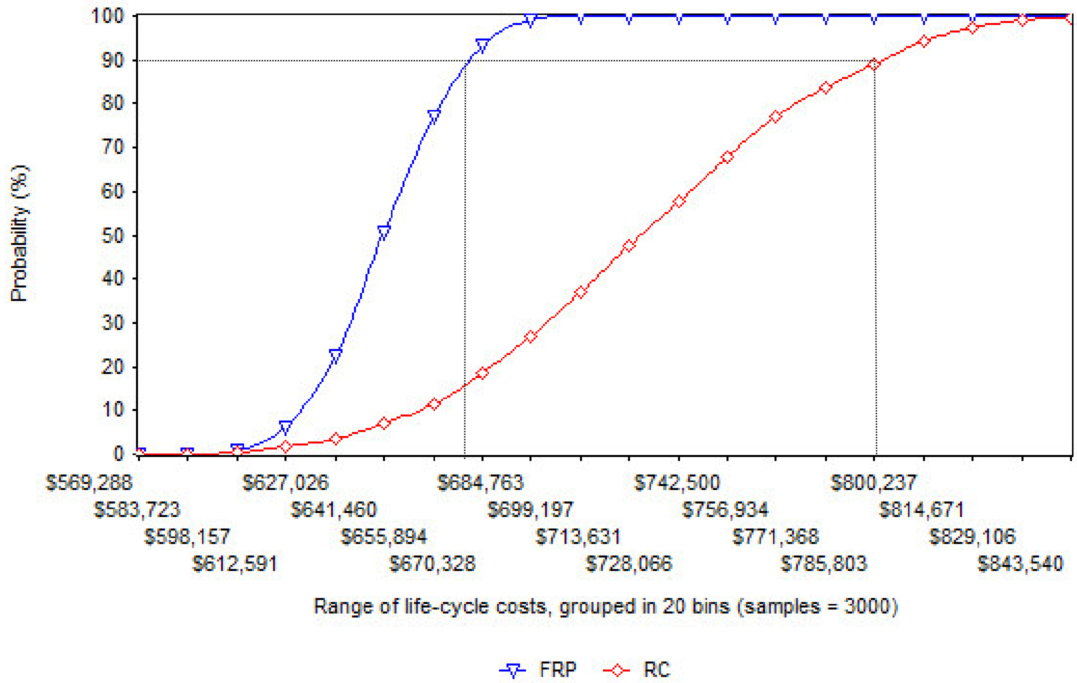

Figure 16 - BridgeLCC 2.0 Total cost cumulative distribution of deck alternatives

Table 10 shows the mean, standard deviation, minimum and maximum values of the total net value costs. These values were obtained through a probabilistic analysis using BridgeLCC 2.0's built in Monte Carlo simulation.

Table 10 - BridgeLCC 2.0 Mean distributions of costs (Monte Caro Simulation)

Total Cost (Present Value)		Base Case - FRP deck Total Costs	Alternative - RC Total Costs
95% confidence interval	lower limit	$595,778	$618,305
	upper limit	$659,012	$788,522
Mean		$626,994	$703,495
Standard Deviation		$19,066	$50,958

Figure 17 shows a graph in form of histogram that visualizes the risk profile for costs for both alternatives. The mean value of normally distributed present values of costs are highlighted as the mean distribution. The area underneath the curves is the probability of occurrence and the curves show the variability of the mean. To each side of the mean three standard deviations are considered. The consideration of these standard deviation cases makes sure that every possible scenario is considered during the risk analysis.

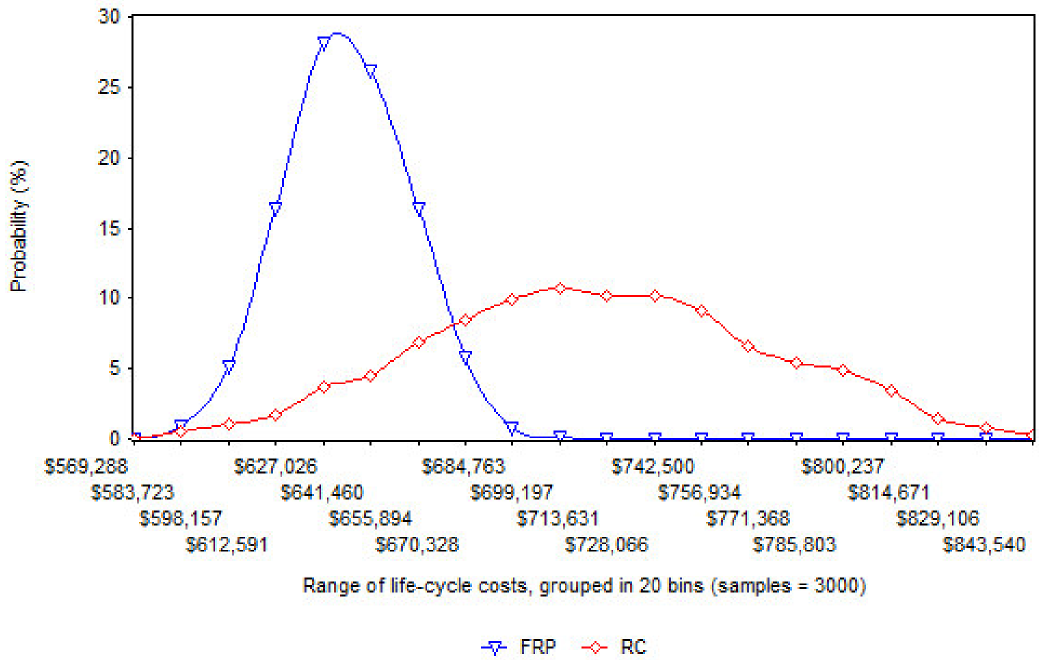

Figure 17 - BridgeLCC 2.0 Total cost distribution of deck alternatives

5.5. Inclusion of Environmental Impacts

The transport of materials has a great impact on the environment due to carbon emissions. Due Rhode Island's coastal geographical location marine transportation of construction material is possible which allows a reduction in carbon emissions compared to ground transportation. Additionally, comparing both alternatives, the transportation of FRP is lower in carbon emission due to its lightness. Lower embodied energy is determined for FRP compared to RC. An example for a bridge with a 40 ft span was displayed in Figure 8. It shows, that FRP possesses the lowest embodied energy while the material per unit amount is in possession of the highest embodied energy.

Applying the shadow prices for the different environmental effect categories presented in Table 3 to the masses of material used for the construction, it will identify lower third-party costs for FRP bridge decks than for RC bridge decks.

Afterwards, these costs need to be implemented into BridgeLCC 2.0 to obtain a sensitivity and risk analysis. Concluding these steps will offer a full LCCA including environmental costs and its sensitivities and risks.

CHAPTER 6

CONCLUSION

6.1. Summary

In this study, a full LCCA has been performed comparing FRP bridge deck costs with a conventional reinforced bridge deck.

To begin with, chapter 2 briefly introduces conventional bridge construction materials. These materials are followed by the more detailed section on FRP. The fiber material used for FRP and their properties are mentioned in section 2.2.1. The importance of the matrix and fiber-matrix bonding are indicated in the following two sections. This chapter ends with the advantages and concerns of FRP in bridge construction.

The life-cycle of a bridge is described in chapter 3. For a reasonable comparison of different design alternatives, costs need to be considered throughout the whole life-cycle of a design. Therefore, LCC can be stated as costs by timing, costs by bearer, or costs by component. This chapter includes equations needed for the calculation of the different cost categories. Additionally, information of environmental impacts is provided which is suggested to be implemented into the LCCA. These costs undergo the sub-category of third-party as the cost bearing party. To do so, Simos' rating system is utilized. Furthermore, four methods to perform LCA are presented. Within this analysis, costs are assigned to each environmental impact due to bridge design. These costs then need to be entered in LCCA to obtain LCC results.

Chapter 4 explains the steps to perform a full LCCA. The deterministic approach is subdivided into five steps. These steps start from establishing alternatives that can be compared and terminated with the analyzation of the results obtained from the LCC computation. The chapter offers the equations to calculate the net present value, which is the sum of initial costs and all discounted cash flows that happen in the past, present, and future, and is needed to convert present and future costs into a common metric. It gives an overview on the discount rates that are used by different countries. In section 4.1.2 the sensitivity approach is explained. The first step of the sensitivity approach is the identification of variables that show significant influence on model outcomes. The second step involves the determination of points that vary. By setting minimum and maximum values with a confidence interval of 95%, the value lies between the set minimum and maximum with a certainty of 95%. A table is given with deviation assumption for specific variables that are entered in the computational analysis software. Risk analysis is explained in the following section. It performs a stochastic analysis and takes over where the sensitivity approach fails. Table 7 states where input variables originate from. The Monte Carlo simulation is a numerical method that accounts for risks in quantitative analysis. This simulation runs the same variables in different combinations over and over to achieve a prediction of exact reactions on certain actions. The chapter rounds off with the introduction of software for each LCCAs (BridgeLCC 2.0) or LCAs (BridgeLCA).

A full LCCA on Canonchet Bridge in Hopkinton, RI is performed in chapter 5. For this LCCA there are two alternatives; an FRP bridge deck was compared with a conventional reinforced concrete bridge deck. All the data that was needed for the analysis was first collected and then entered in the software BridgeLCC 2.0 which is available from NIST at no cost. The costs for each analysis were categorized by the time of the cost and then sub-categorized into the bearer of the cost. The costs are presented in each section and a list of all costs can be found in the appendix. After completing the deterministic approach, the sensitivity analysis and risk analysis are performed. These results are presented are presented in this chapter.

6.2. Discussion

The scope of this study is to examine the viability as well as the economic efficiency of FRP bridge decks in comparison with bridge decks using conventional materials. The analysis is conducted as planned, in which bridge data from Ehlen & Marshall is used. The given data is adjusted to measurements and location data of the analyzed bridge in Hopkinton, RI. The software BridgeLCC 2.0 that is used for the analysis obtains a deterministic analysis and investigates the costs for two design alternatives. In the base case the bridge deck was designed with FRP and the alternative which is referred to as alternative 1 is designed with reinforced concrete. Due to previously made assumptions, deviations and uncertainties in unit costs and unit amounts, a sensitivity analysis is performed. To understand the consequences of multiple risks acting together, a risk analysis is conducted. Taking uncertainties and risks into consideration, the total costs including agency and user costs throughout the whole life-cycle determine FRP to be a more economical alternative. Environmental costs were not yet included but needed data for an analysis was collected and needs to be expanded to include it to an LCCA.

Environmental costs are predicted to influence total costs of FRP positively compared to the RC alternative.

When comparing the results of the deterministic approach for the base case and alternative 1, the costs for a service life of 75 years are about the same for both alternatives. The price difference increases when uncertainties and risks are considered, and a sensitivity and risk analysis are performed. With the inclusion of risks and uncertainties, the FRP bridge deck alternative turns out to be the cheaper alternative compared to the RC bridge deck alternative.

6.3. Limitation of this Study

An appropriate scope of the study and concerns regarding the applicability are discussed in this section. Controversial aspects will be highlighted, and potential future research objectives can be found in the following section.

While FRP is already commonly used in aerospace engineering it is still slowly gaining attention in the civil engineering industry. Due to missing design codes for the material and the lack of experience with FRP in construction, Civil Engineers are not comfortable enough to use the material for ordinary designs. These issues can be improved by the development of a design code for FRP bridges. LCC can only vaguely determine actual costs that happen throughout the whole design life. Especially future costs including user and third-party costs can only be estimated. Economic development, inflation and the progress in technology and experience cannot be estimated. This is very important since all these factors have an influence on costs that appear in the future. The assumptions and estimations create a huge range in values.

This leads to a very unspecific analysis and therefore, computational software is needed to obtain applicable results when conducting a sensitivity approach.

The main obstacle of FRP bridge design is the lack of design-knowledge and the difficulty of cost prediction. The lack of accessible data of FRP bridge designs and the material itself lead to many assumptions and estimations. If authorities and manufacturers will be more transparent with researching institutions and share data, FRP and other new materials could speed up to be established on the market.

Another obstacle of FRP bridge design is the knowledge about deterioration. Not much is known about how fast FRP is deteriorating and therefore, periods of maintenance and repair throughout the life-cycle are set to be safe.

6.4. Conclusion & Future Work

In conclusion, the proposed analysis proved its ability to evaluate bridge deck designs according to costs carried by different stakeholders. Furthermore, environmental impacts of the bridge alternatives are included in the analysis. The performed analysis shows, that FRP is a competitively viable material for bridge deck construction. Bridges and other constructions in the State of Rhode Island are subjected to cold winters with many freeze-thaw cycles, aggressive de-icing chemicals and corrosion due to coastal air. Therefore, FRP is a suitable material to prevent bridge decks from these impacts in Rhode Island. Additionally, the use of FRP allows the bridge to be repaired and maintained less frequently than current materials. Naturally this results in lower maintenance costs and less frequent construction. A full analysis, including a deterministic approach, sensitivities and risks, was performed for two alternatives to observe the materials FRP and RC for bridge decks. Environmental impacts were not included but were introduced.

To obtain a more specific LCCA cost prediction, further work should focus on deterioration of FRP bridge decks. The LCCA analysis can be extended from focusing bridge decks only to superstructures or complete bridge structures.

Future work should include environmental impacts in the LCCA as introduced in section 3.2. Therefore, proposed costs for every potential should be applied to every item and get adjusted accordingly with the Simos' rating system. Some environmental factors would be the global warming potential (GWP), ozone depletion (ODP), terrestrial acidification (AP), freshwater eutrophication (EP), fossil depletion (FD), human toxicity cancer (HTC), human toxicity non-cancer (HTNC) and ecotoxicity (ET) all of which should be considered. An inclusion of these factors in BridgeLCC 2.0 will also conduct a sensitivity and risk analysis of these environmental impacts. It is expected, that once all environmental impact costs are implemented correctly, FRP bridges decks show a significant advantage over conventional bridge deck materials.

APPENDICES

APPENDIX A

Table 11 - Spreadsheet for LCCA determinisitic calculation (Setunge et al. 2002)

Year / Costs	Number	Unit cost 1000 $	Total 1000 $	1	2	3
Initial cost						
Preliminary design cost						
Start up cost						
Raw material cost						
FRP sheets						
Labour cost						
Supervisors and technicians						
Other skilled workers						
Unskilled workers						
Maintenance cost						
Inspection						
Annual maintenance						
Material cost						
Labour cost						
Traffic control cost						
Repair cost						
Material cost						
Labour cost						
Traffic control cost						
User cost						
Work zone user cost						
During initial rehabilitation						
During maintenance						
Failure cost						
Probability of failure						
Cost of failure						
Damages						
Loss of life						
Injury						
Total						

Sensitivity analysis

Discount rate

Discount rate (%)	NPV ($)	IRR (%)
4		

Initial cost

Initial cost (%)	NPV ($)
75	
100	
125	

Road usage

Road usage	NPV ($)
High	
Medium	
Low	

APPENDIX B

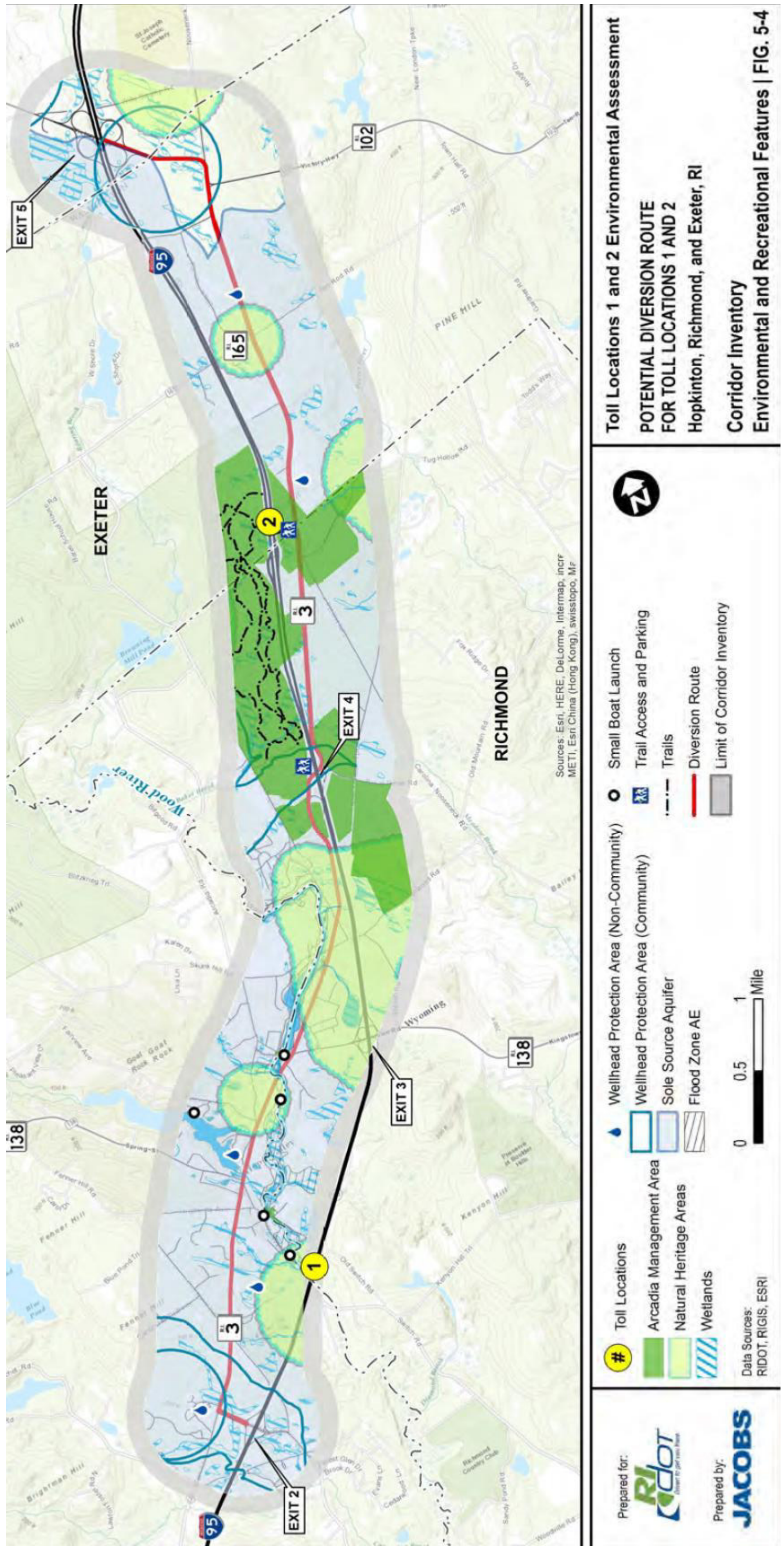

Figure 18 - Circumvention Plan (RIDOT et al. 2017)

APPENDIX C

Data: Individual Costs

07/08/2018

Item	Event	Start Year	End Year	Frequency	Qtty	Unit of Measure	Unit Cost	Total Cost	Remarks
Base Case									
Agency									
Initial Construction									
Factory Fab	<no event>	1	1	1.0000	9601.000	Area of	$ 34	$ 324,034	
Shipping	<no event>	1	1	1.0000	1.000	LS	$ 30,750	$ 30,750	
5% beam surcharge	<no event>	1	1	1.0000	1.000	LS	$ 8,248	$ 8,248	
On-site fab: bearings	<no event>	1	1	1.0000	1.000	LS	$ 6,111	$ 6,111	
On-site fab: install	<no event>	1	1	1.0000	9601.000	Area of	$ 8	$ 78,248	
F&I metal guard rail	<no event>	1	1	1.0000	284.000	LF	$ 8	$ 2,315	
F&I median	<no event>	1	1	1.0000	142.000	LF	$ 33	$ 4,628	
Polymer concrete asphalt	<no event>	1	1	1.0000	9601.000	Area of	$ 3	$ 31,299	
Pre-design NTM project	<no event>	1	1	1.0000	50.000	LHRS	$ 81	$ 4,074	
Academic design consultant	<no event>	1	1	1.0000	1.000	LS	$ 32,589	$ 32,589	
Labratory tests	<no event>	1	1	1.0000	1.000	LS	$ 41,551	$ 41,551	
Meeting with fabricator	<no event>	1	1	1.0000	60.000	LHRS	$ 81	$ 4,888	
Field engineer	<no event>	1	1	1.0000	100.000	LHRS	$ 81	$ 8,147	
O, M, and R									
Deck inspection 1st year:	<no event>	1	1	1.0000	336.000	LHRS	$ 49	$ 16,424	
Deck inspection year 2-4:	<no event>	2	4	1.0000	56.000	LHRS	$ 49	$ 2,737	
Deck inspection year 4-73:	<no event>	5	73	2.0000	28.000	LHRS	$ 49	$ 1,369	
Supplementary inspection	<no event>	5	73	2.0000	1.000	LS	$ 0	$ 0	
Deck replacement	<no event>	50	50	1.0000	9601.000	Area of	$ 5	$ 50,021	
Polymer concrete patching	<no event>	25	70	25.0000	650.000	LF	$ 3	$ 2,119	
develop non-destructive	<no event>	25	70	25.0000	40.000	LHRS	$ 81	$ 3,259	
Disposal									
Disposal of deck	<no event>	75	75	1.0000	150.000	LHRS	$ 24	$ 3,666	

BridgeLCC 2.0

Table 12 - BridgeLCC 2.0 Costs - FRP Deck (pg. 1)

Data: Individual Costs

07/08/2018

Item	Event	Start Year	End Year	Frequency	Qtty	Unit of Measure	Unit Cost	Total Cost	Remarks
Dump fee	<no event>	75	75	1.0000	1.000	LS	$ 11,610	$ 11,610	
User									
Initial Construction									
Construction: I95 driver delay,	<no event>	1	1	1.0000	5.000	day(s)	$ 10,723	$ 53,617	
Construction: CAR driver delay,	<no event>	1	1	1.0000	5.000	day(s)	$ 175	$ 876	
O, M, and R									
Inspection 1st year: driver	<no event>	25	25	1.0000	12.000	day(s)	$ 52	$ 627	
Inspection year 2-4: driver	<no event>	2	4	1.0000	2.000	day(s)	$ 86	$ 172	
Inspection year 5-73: driver	<no event>	5	73	2.0000	1.000	day(s)	$ 80	$ 80	
Deck replacement: driver delay,	<no event>	50	73	25.0000	3.000	day(s)	$ 30	$ 91	
Disposal									
Disposal: CAR driver delay,	<no event>	75	75	1.0000	5.000	day(s)	$ 36	$ 178	
Disposal: I95 driver delay,	<no event>	75	75	1.0000	5.000	day(s)	$ 2,177	$ 10,884	

NIST BridgeLCC 2.0

Table 13 - BridgeLCC 2.0 Costs - FRP Deck (pg. 2)

APPENDIX D

Data: *Individual Costs*

07/08/2018

Item	Event	Start Year	End Year	Frequency	Qtty	Unit of Measure	Unit Cost	Total Cost	Remarks
Alternative #1									
Agency									
Initial Construction									
Construction of new deck	<no event>	1	1	1.0000	9601.000	Area of	$ 24	$ 234,648	
O, M, and R									
Deck inspection	<no event>	1	73	2.0000	56.000	LHRS	$ 49	$ 2,737	
Resurface 5% of deck	<no event>	15	74	25.0000	480.000	SF	$ 16	$ 7,819	
Resurface 2.5% of deck	<no event>	10	74	15.0000	240.000	SF	$ 16	$ 3,910	
Resurface complete deck	<no event>	25	74	25.0000	9601.000	Area of	$ 16	$ 156,400	
Disposal									
Disposal of deck	<no event>	75	75	1.0000	9601.000	Area of	$ 24	$ 234,648	
User									
Initial Construction									
Construction: I95 driver delay,	<no event>	1	1	1.0000	21.000	day(s)	$ 10,723	$ 225,190	
Construction: CAR driver delay,	<no event>	1	1	1.0000	21.000	day(s)	$ 175	$ 3,680	
O, M, and R									
Deck inspection: CAR driver	<no event>	2	73	2.0000	2.000	day(s)	$ 86	$ 172	
Disposal									
Disposal: CAR driver delay,	<no event>	75	75	1.0000	10.000	day(s)	$ 2,177	$ 21,768	
Disposal: I95 driver delay,	<no event>	75	75	1.0000	10.000	day(s)	$ 2,177	$ 21,768	

BridgeLCC 2.0

Table 14 - BridgeLCC 2.0 Costs - RC Deck

APPENDIX E

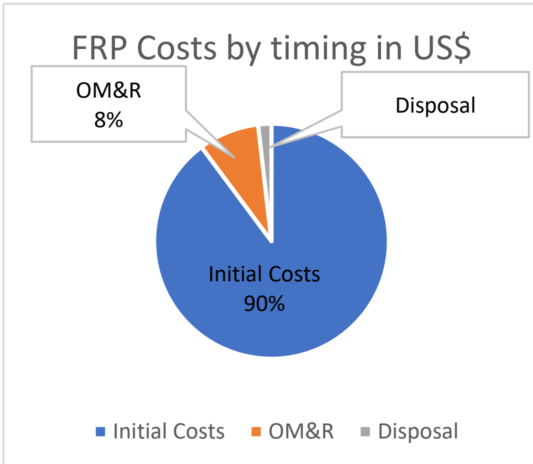

Figure 19 - FRP Costs by timing in US$

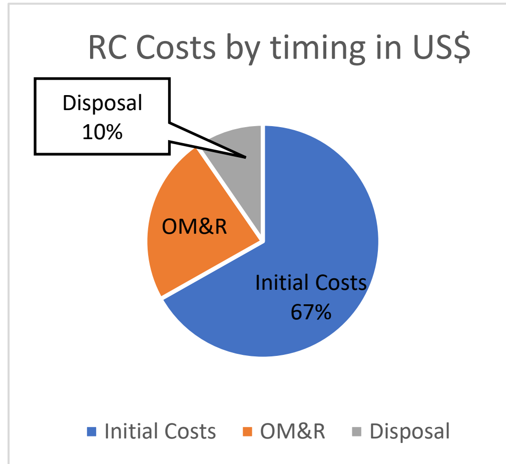

Figure 20 - RC Costs by timing in US$

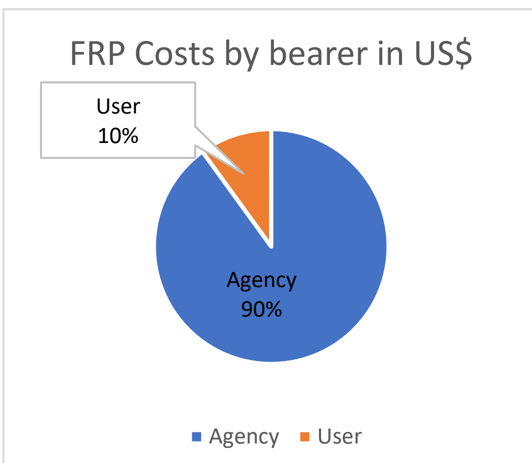

Figure 21 - FRP Costs by bearer in US$

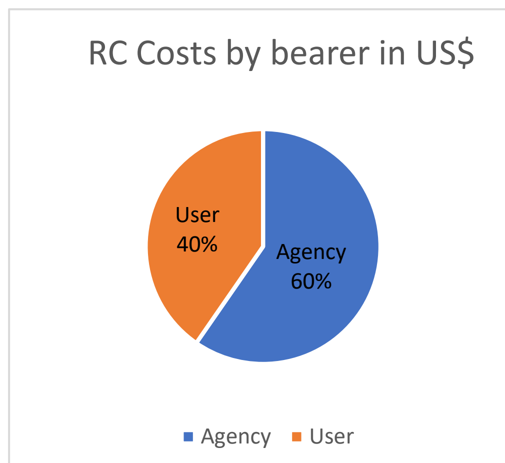

Figure 22 - RC Costs by bearer in US$

APPENDIX F

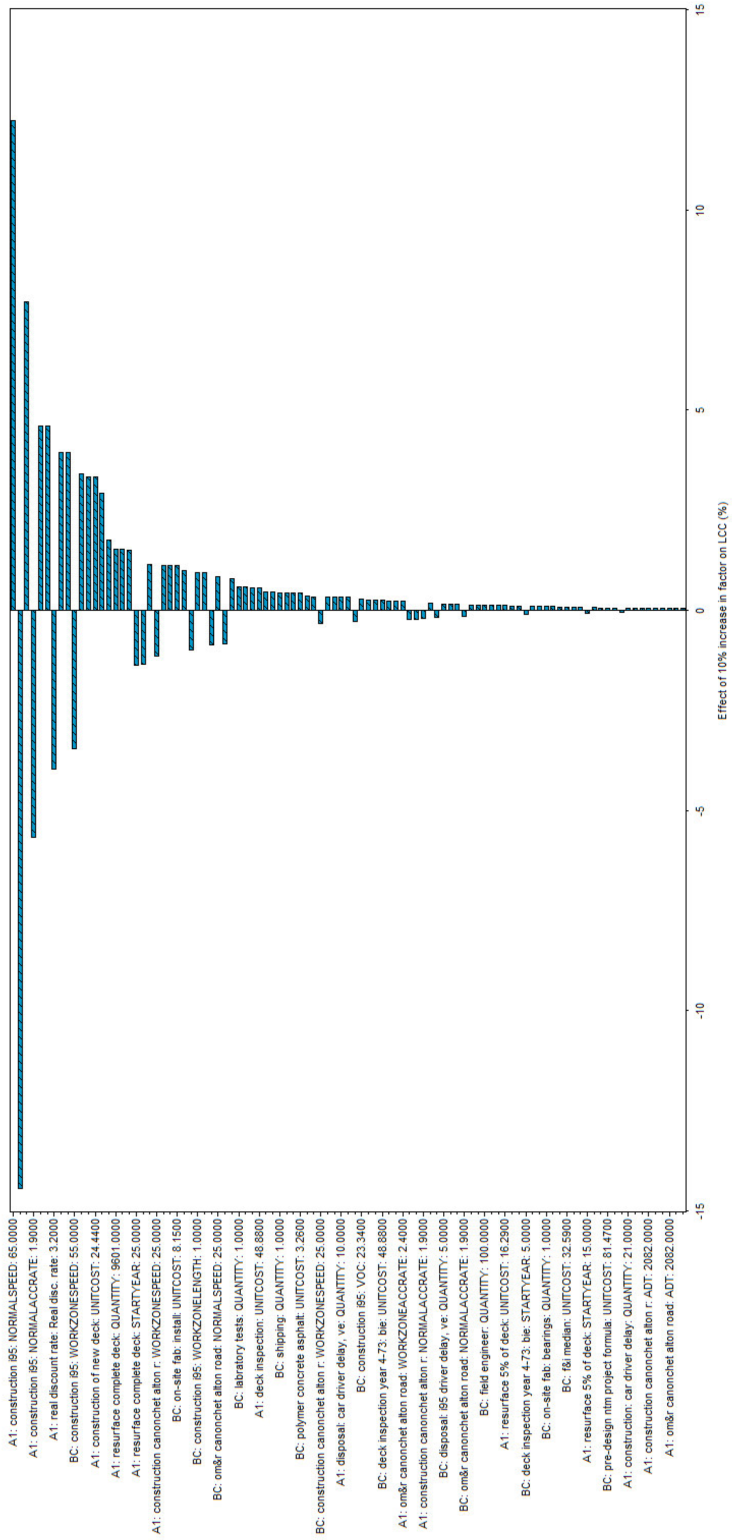

Figure 23 - BridgeLCC 2.0 Sensitivity analysis all results by effect

APPENDIX G

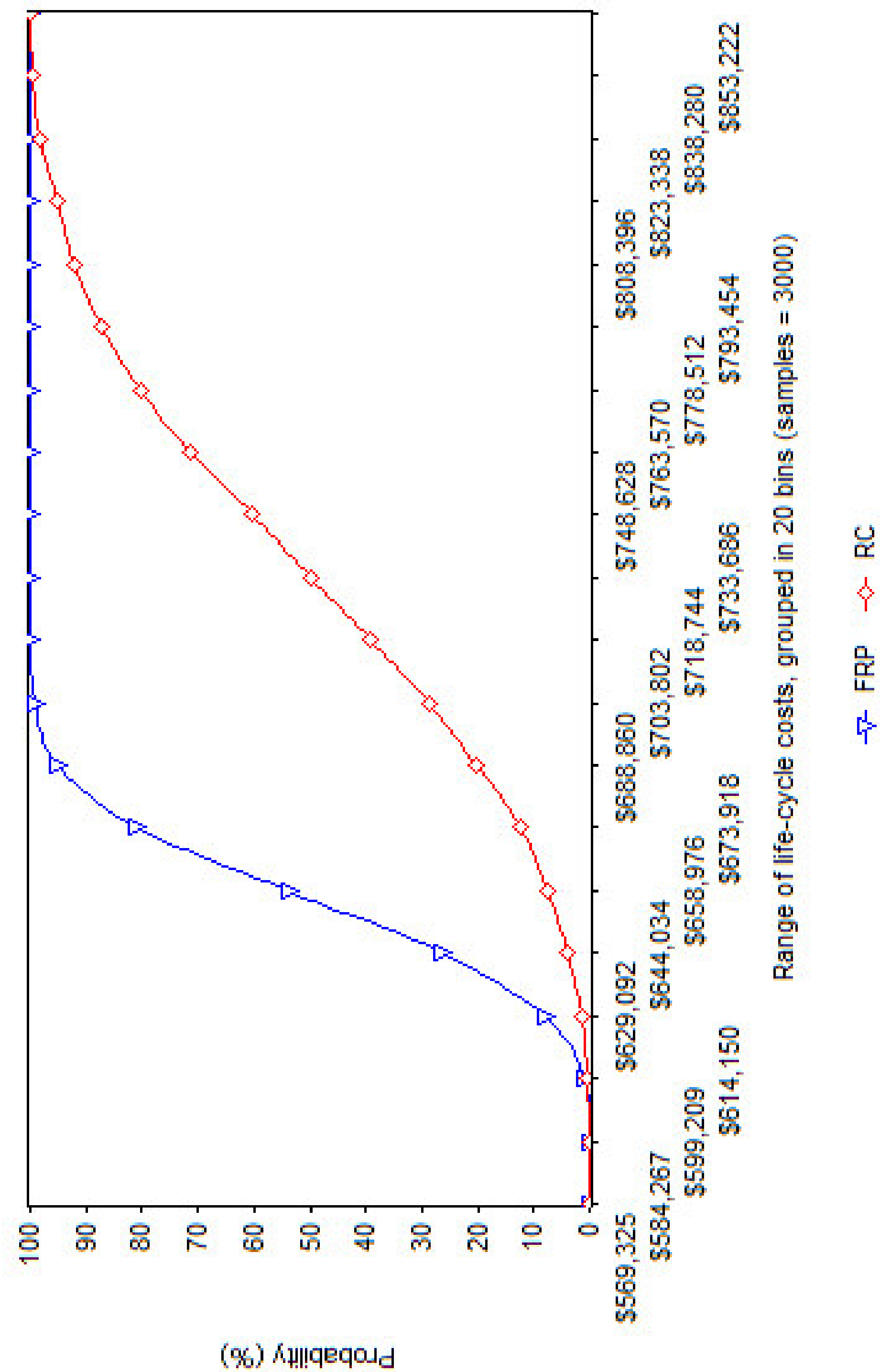

Figure 24 - Monte Carlo Simulation - Cumulative Diagram - 3000 samples

APPENDIX H

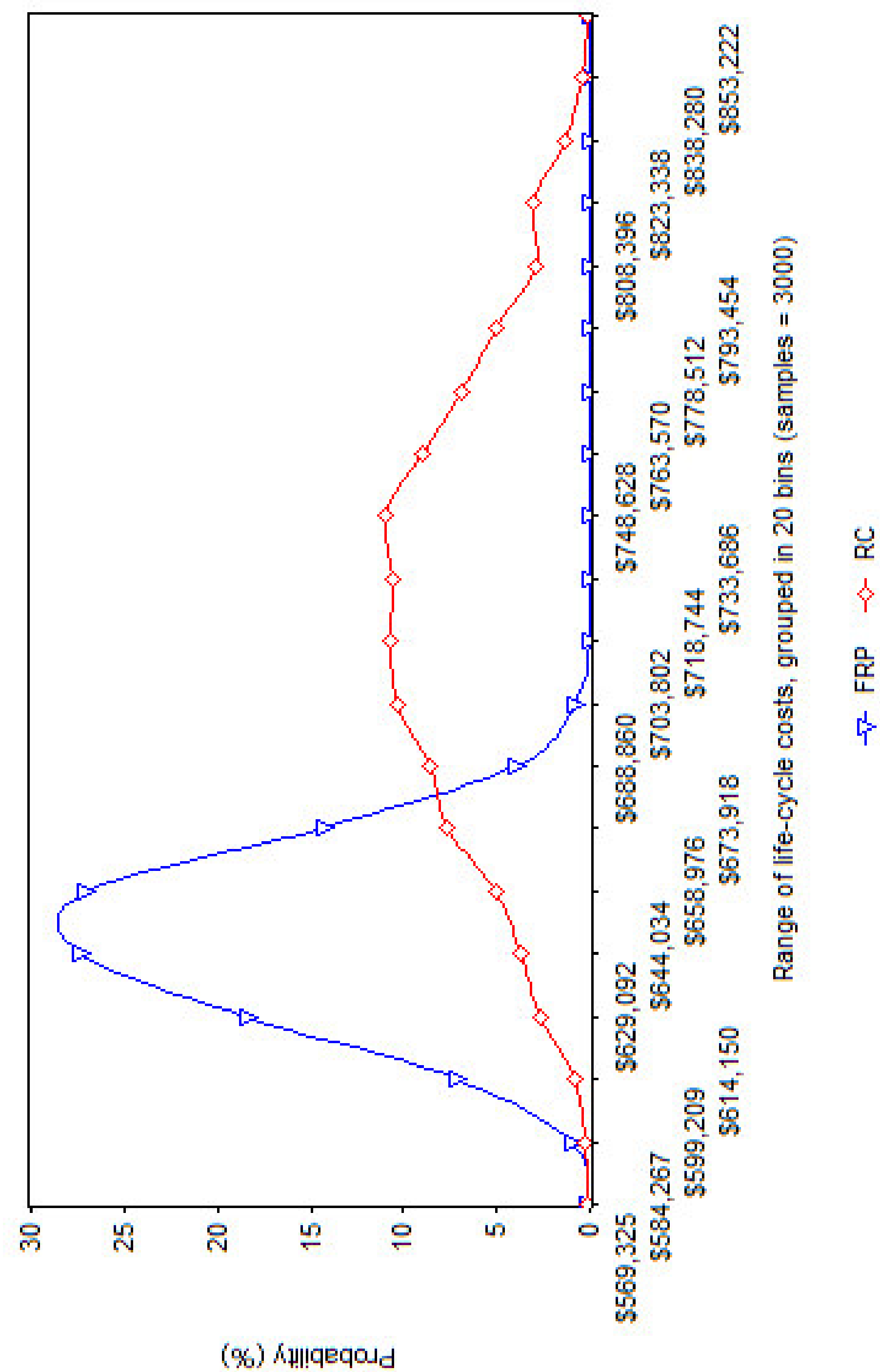

Figure 25 - Monte Carlo Simulation - 3000 samples

APPENDIX I

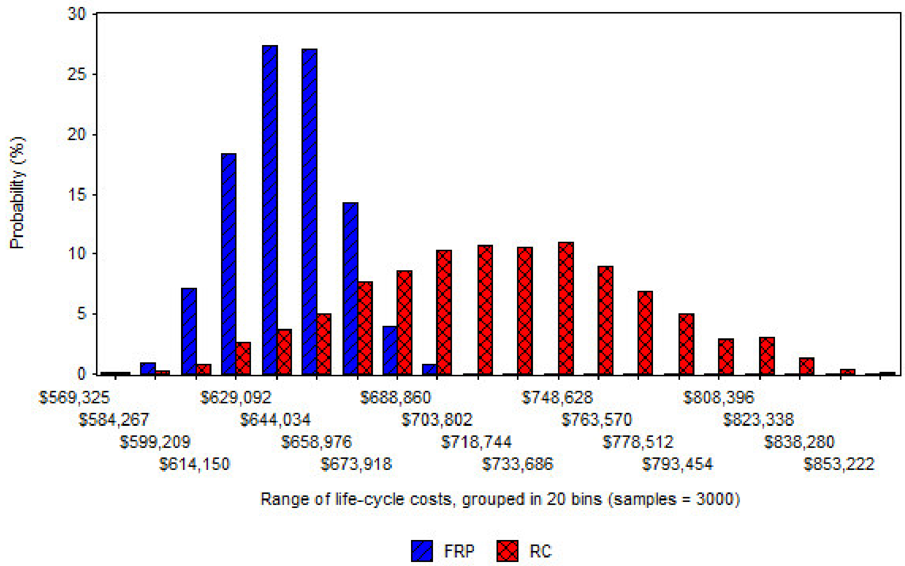

Figure 26 - Monte Carlo Simulation - 3000 samples

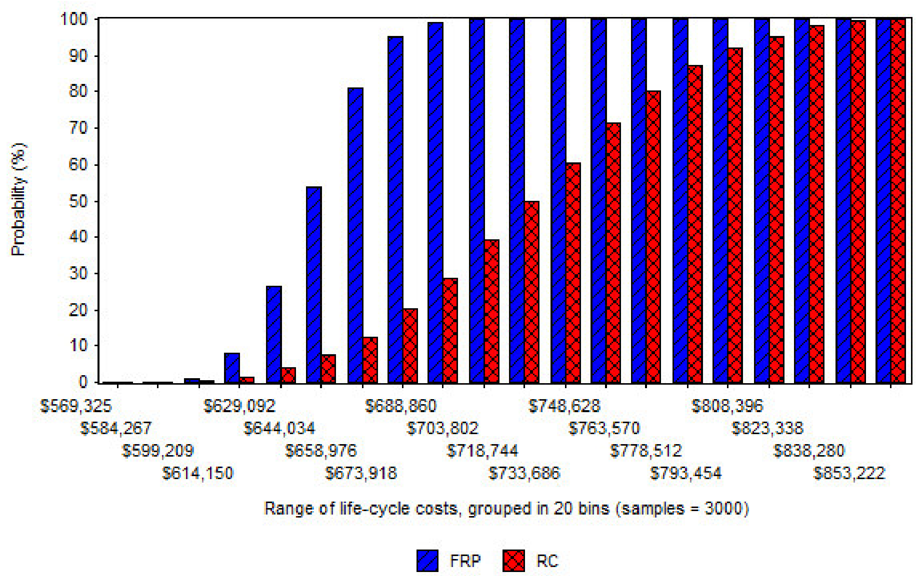

Figure 27 - Monte Carlo Simulation - 3000 samples - cumulative

APPENDIX J

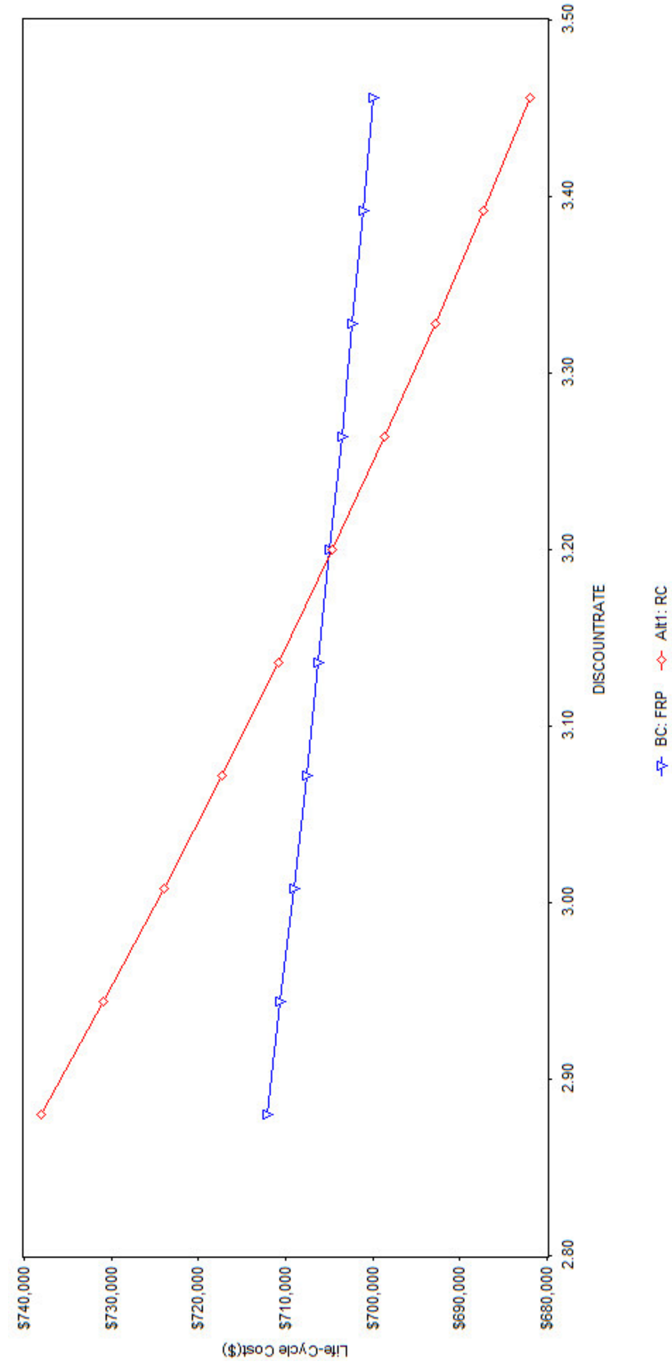

Figure 28 - Influence of discount rate on total costs

BIBLIOGRAPHY

Aktan, A. Emin, Culmo, Michael P., Frangopol, Dan M., French, Catherine W., Rabbat, Basile G., Ralls, Mary Lou, Russell, Henry G., Sanders, David H., Showers, Joseph, Tadros, Maher K., Woods, and Stanley W. "Concrete Bridges.".

Arnold, S. F., and Carr, H. (2010). "FRP Strengthening: What designers need to know." *Concrete International.*

Azizinamini, A., Power, E. H., Myers, G. F., Ozyildirim, H. C., Kline, E. S., Whitmore, D. W., and Mertz, D. R. (2013). *Design Guide for Bridges for Service Life*, Transportation Research Board, Washington, D.C.

Bianquis, R. J. (2015). *Assessment methodology for environmental impact of bridges,* Master of Engineering, Massachusetts Institute of Technology.

Bosman, J. (2015). *FRP Road Bridges as a Concrete Alternative: Determining life cycle costs of all-FRP and concrete road bridges using a parametric calculation tool,* Master Thesis, University of Twente.

Christensen, P. N., Sparks, G. A., and Kostuk, K. J. (2005). "A method-based survey of life cycle costing literature pertinent to infrastructure design and renewal." *Can. J. Civ. Eng.*, 10.1139/l04-077, 250–259.

Denise, W. (2016). *The Value of Travel-Time: Estimates of the Hourly Value of Time for Vehicles in Oregon 2015* (Jun. 14, 2018).

Department of Transport and Main Roads (2011). *Cost-benefit analysis manual road projects: Transportation and Main Roads* (Apr. 28, 2018).

Ehlen, M. A., and Marshall, H. E. (1996). *The Economics of New-Technology Materials: A Case Study of FRP Bridge Decking*, Gaithersburg, MD (Jun. 19, 2018).

FHWA. (2011). "Roadway Departure Safety - Safety | Federal Highway Administration." <https://safety.fhwa.dot.gov/local_rural/training/fhwasa1109/app_c.cfm> (Jul. 6, 2018).

FHWA (2013). "Financial Structuring and Assessment for Public–Private Partnerships: A Primer.".

FHWA. (2017). "Deficient Bridges by Highway System 2017: National Bridge Inventory." <https://www.fhwa.dot.gov/bridge/nbi/no10/defbr17.cfm> (Apr. 11, 2018).

FHWA. (2018). "Tables of Frequently Requested NBI Information: National Bridge Inventory." <https://www.fhwa.dot.gov/bridge/britab.cfm> (Apr. 11, 2018).

Foster, D. C., Richards, D., and Bogner, B. R. (2000). "Design and Installation of Fiber-Reinforced Polymer Composite Bridge." *Journal of Composites for Construction*, 10.1061/(ASCE)1090-0268(2000)4:1(33), 33–37.

Hartman, D., Greenwood, M. E., and Miller, D. M. (1996). *High Strength Glass Fibers* (Apr. 16, 2018).

Hatami, A., and Morcous, G. (2013). *Life-Cycle Assessment of Nebraska bridges*, Omaha, NE (Jun. 27, 2018).

Hawk, H. (2003). *Bridge life-cycle cost analysis*, Transportation Research Board National Research Council, Washington, D.C.

Henkel, D. P., and Pense, A. W. (2002). *Structure and properties of engineering materials*, McGraw-Hill, Boston, Mass.

Karbhari, V. M., and Zhao, L. (2000). "Use of composites for 21st century civil infrastructure." *Computer Methods in Applied Mechanics and Engineering*, 10.1016/S0045-7825(99)90270-0, 433–454.

Kirk, R. S., and Mallett, W. J. (2018). "Highway Bridge Conditions: Issues for Congress.".

Lee, S. W., Hong, K. J., and Park, S. (2018). "Current and Future Applications of Glass-Fibre-Reinforced Polymer Decks in Korea." *Structural Engineering International*, 10.2749/101686610793557672, 405–408.

Mara, V., Haghani, R., and Harryson, P. (2014). "Bridge decks of fibre reinforced polymer (FRP): A sustainable solution." *Construction and Building Materials*, 10.1016/j.conbuildmat.2013.09.036, 190–199.

Mara, V., Haghani, R., and Sagemo, A. e. a. (n.d.). "Comparitive Study of different bridge concepts based on life-cycle cost analysis and life-cycle assessment.".

Martin, B. T. (2015). "Highway bridges: Linking Funding to Conditions May Help Demonstrate Impact of Federal Investment." *Innovative bridge design handbook: Construction, rehabilitation and maintenance,* A. Pipinato, ed., Butterworth-Heinemann is an imprint of Elsevier, Kidlington, Oxford, UK, 483–508.

Mufti, A. A., and Neale, Kenneth, W. (2008). "State-of-the-Art of FRP and SHM Applications in Bridge Strucures in Canada.", 2(2), 60–69.

National Association of Corrosion Engineers. "Highways and Bridges: Corrosion Ressources for Highways and Bridges." <https://www.nace.org/Corrosion-Central/Industries/Highways-and-Bridges/> (May. 3, 2018).

Nystrom, H. E., Watkins, S. E., Nanni, A., and Murray, S. (2003). "Financial Viability of Fiber-Reinforced Polymer (FRP) Bridges." *Journal of Management in Engineering*, 10.1061/(ASCE)0742-597X(2003)19:1(2), 2–8.

Oregon State University. (n.d.). "Analysis of Accident Statistics." (Jun. 14, 2018).

Ozcoban, E. (2017). *Comparison of Reinforced Concrete Bridge and Fiber Reinforced Polymer Bridge Using Life Cycle Assessment,* Master-Thesis, University of Miami.

Ozturk, O. (2013). *Estimating the Impact of Work Zones on Highway Safety*, Transportation Research Record, Journal of Transportation Research Board (Jun. 14, 2018).

Pipinato, A., ed. (2015). *Innovative bridge design handbook: Construction, rehabilitation and maintenance*, Butterworth-Heinemann is an imprint of Elsevier, Kidlington, Oxford, UK.

RIDOT (2017). "General Provisions - Contract Specific.".

RIDOT, U.S. Department of Transportation, and FHWA (2017). *Environmental Assessment: Toll Locations 1 and 2 Toll Location 1 and 2 - Hopkinton, Richmond, and Exeter, Rhode Island Rhode Island* (Jun. 14, 2018).

Saeedi, A., Emami, S., Doolen, T. L., and Tang, B. (2013). "A decision tool for accelerated bridge construction." *pcij*, 10.15554/pcij.03012013.48.63, 48–63.

Sagemo, A., and Storck, L. (2013). *Comparative study of bridge concepts based on life-cycle cost analysis and lifecycle assessment,* Chalmers University of Technology.

Salokangas, L. (2009). *ETSI Project (Stage 2): Bridge Life Cycle Optimisation*, Finland.

Setunge, S., Lokuge, W., and Nezamian, A. (2002). *Whole of life cycle cost analysis in bridge rehabilitation.doc: Report 2002-005-C-03* (Apr. 27, 2018).

Song, Y. S., Youn, J. R., and Gutowski, T. G. (2009). "Life cycle energy analysis of fiber-reinforced composites." *Composites Part A: Applied Science and Manufacturing*, 10.1016/j.compositesa.2009.05.020, 1257–1265.

Sonnenschein, R., Gajdosova, K., and Holly, I., eds. (2016). *FRP Composites and their Using in the Construction of Bridges*.

Steere Engineering (2017). *Narragansett Pier Middle School Pedestrian Brdige over Crooked Brook*, Warwick, RI (Jun. 20, 2018).

Sugiyama, S. (2008). "Monte Carlo Simulation / Risk Analysis on a spreadsheet: Review of three software packages.", (9), 36–42.

The Constructor. (2017a). "Materials Used for Bridge Construction: Materials Used in Bridge Construction." <https://theconstructor.org/structures/materials-used-bridge-construction/20428/> (May. 3, 2018).

The Constructor. (2017b). "Prestressed Concrete Principles, Need, Advantages and Disadvantages." <https://theconstructor.org/concrete/prestressed-concrete-principles-advantages/28/> (May. 3, 2018).

Thoft-Christensen, P. (2009). "Life-cycle cost-benefit (LCCB) analysis of bridges from a user and social point of view." *Structure and Infrastructure Engineering*, 10.1080/15732470701322818, 49–57.

WSDOT (2014). "WSDOT's Handbook for Corridor Capacity Evaluation.", 1, 48.

Zhang, C., Amaduddin, M., and Canning, L. (2011). "Carbon dioxide evaluation in a typical bridge deck replacement project." *Institiution of Civil Engineers*, 164(EN4), 12.